EFFECT OF CRUSHED-GRAVEL FINE AGGREGATE ON THE STRENGTH OF BITUMINOUS SURFACE MIXTURES

FEBRUARY, 1956
No. 6

by

Robert P.
Lottman

Joint
Highway
Research
Project

PURDUE UNIVERSITY
LAFAYETTE INDIANA

EFFECT OF CRUSHED-GRAVEL FINE AGGREGATE
ON THE STRENGTH OF BITUMINOUS SURFACE MIXTURES

TO: K. B. Woods, Director
Joint Highway Research Project

February 1, 1956

File: 14-2-3-34
C-139

FROM: Harold L. Michael, Assistant Director

The attached report entitled "Effect of Crushed-Gravel Fine Aggregate on the Strength of Bituminous Surface Mixtures" was prepared by Mr. R. P. Lottman and used as a thesis for the degree of M.S.C.E. This work was accomplished in the bituminous laboratory under the supervision of Professor Goetz and was performed under a fellowship sponsored by the National Sand and Gravel Association. It is being presented to the Advisory Board as a matter of information.

The crushed gravel fine aggregate used in the study was obtained from the American Aggregates Corporation in Indianapolis and is the same material that has been widely used by the city of Indianapolis in their bituminous paving work. Thus the results of the study have direct application. It is indicated that crushed fine aggregate produced from gravel may be used to increase the stability of certain dense graded bituminous surfacing mixtures as measured by laboratory evaluation. We are sure that the members of the Advisory Board will find the results of this study of interest.

Respectfully submitted,

Harold L. Michael
cg

Harold L. Michael, Assistant Director
Joint Highway Research Project

HLM:cjg

Attachment

cc: J. R. Cooper
J. T. Hallett
F. F. Havey
G. A. Hawkins
G. A. Leonards
B. B. Lewis
R. E. Mills
B. H. Petty
Lloyd Poindexter
C. E. Vogelgesang
J. L. Waling

Digitized by the Internet Archive
in 2011 with funding from
LYRASIS members and Sloan Foundation; Indiana Department of Transportation

http://www.archive.org/details/effectofcrushedg00lott

EFFECT OF CRUSHED-GRAVEL FINE AGGREGATE
ON THE STRENGTH OF BITUMINOUS SURFACE MIXTURES

BY

R. P. Lottman
Graduate Fellow
Joint Highway Research Project

File: 14-2-3-34
C-139

Purdue University
Lafayette, Indiana

February 1, 1956

ACKNOWLEDGMENTS

This investigation was carried out at Purdue University under a Fellowship financed by the National Sand and Gravel Association of Washington, D.C., and with the cooperation of their Director of Engineering, Mr. Stanton Walker.

The writer wishes to express his deepest appreciation for the priviledge of working under a Fellowship sponsored by the Association and for Mr. Walker's assistance in this study.

Most genuine gratitude also goes to Professor William H. Goetz whose assistance and patient counsel have been invaluable assets throughout the undertaking.

The generosity and help of Mr. John F. McLaughlin and Mr. Leonard E. Wood in the laboratory are gratefully acknowledged.

This investigation was conducted in the Bituminous Materials Laboratory of the Joint Highway Research Project of Purdue University. The writer is extremely grateful for the apparatus, special equipment, and part-time student help provided by the Joint Highway Research Project.

The asphaltic materials were supplied by the Standard Oil Company of Indiana, and the mineral aggregates were supplied by the Raymond Street Plant of the American Aggregates Corporation, Indianapolis, Indiana, the Western Indiana Gravel Company, Lafayette, Indiana, and from the National Sand and Gravel Association through their laboratory at the University of Maryland.

TABLE OF CONTENTS

Page

LIST OF TABLES.. v

LIST OF ILLUSTRATIONS....................................... vi

ABSTRACT.. vii

INTRODUCTION.. 1

REVIEW OF THE LITERATURE.................................... 4

Characteristics of Bituminous Surface Mixtures.............. 5

Aggregate Shape and Stability............................... 6

Fine Aggregate Factors Affecting Mixture Strength........... 8

Corps of Engineers' Design Test............................. 11

Triaxial Compression Test................................... 13

ASTM Compression Test....................................... 18

[illegible]... 21

Mineral Aggregate... 21

Bituminous Binder... 34

APPARATUS AND PROCEDURE..................................... 35

Preparation of the Aggregate................................ 35

The Corps of Engineers' Design Procedure for Determining Asphalt Content.. 38

Preparation of the Test Specimens........................... 43

Testing the Specimens....................................... 50

Extraction Tests for Determining Asphalt Distribution....... 58

RESULTS... 65

Mixture Density and Design Data............................. 66

Page

Strength Test Results of Controlled Dense-Graded Bituminous-Concrete Mixtures.............................. 71

Strength Test Results of Controlled Dense-Graded Sand-Asphalt Mixtures.. 73

Strength Test Results of Bituminous-Concrete Mixtures within ASTM Specifications...................... 75

Comparison of Bituminous-Concrete and Sand-Asphalt Triaxial Strength Characteristics........................ 77

SUMMARY OF RESULTS AND CONCLUSIONS.......................... 85

SUGGESTIONS FOR ADDITIONAL RESEARCH......................... 89

APPENDIX A.. 90

Derivation of Relationship Between the Plot of Compressive Strength vs. Lateral Pressure and Mohr's Rupture Envelope. 90

APPENDIX B.. 93

Corps of Engineers' Design Data........................... 94

Triaxial Test Data.. 96

ASTM and Modified ASTM Test Data.......................... 98

Asphalt Extraction Test Data.............................. 101

LIST OF REFERENCES.. 102

LIST OF TABLES

Table Page

1. Specifice Cravity and Absorption of Aggregate........... 26

2. Sieve Analysis of Dense-Graded Bituminous-Concrete and Sand-Asphalt Mixtures................................ 30

3. Sieve Analysis of Crusher Dust and Indiana No. 17 Sand.. 31

4. Gradation of Gravel and Blends of Crusher Dust-Indiana No. 17 Sand within ASTM Specifications for Bituminous-Concrete Mixtures......................... 33

5. Design Asphalt Contents of Bituminous-Aggregate Mixtures. 67

6. Corps of Engineers' Design Data (Bituminous-Concrete and Sand-Asphalt Mixtures, Controlled Dense Grading).............................. 94

7. Corps of Engineers' Design Deta (Crusher Dust-Natural Aggregate Blends within ASTM Specifications for Bituminous-Concrete Mixtures)....... 95

8. Triaxial Test Results (Bituminous-Concrete and Sand-Asphalt Mixtures, Controlled Dense-Grading)............................... 96

9. Triaxial Test Results (Crusher Dust-Natural Aggregate Blends within ASTM Specifications for Bituminous-Concrete Mixtures)....... 97

10. ASTM and Modified ASTM Test Results (Bituminous-Concrete Mixtures, Controlled Dense Grading. 98

11. ASTM and Modified ASTM Test Results (Sand-Asphalt Mixtures, Controlled Dense Grading......... 99

12. ASTM and Modified ASTM Test Results (Crusher Dust-Natural Aggregate Blends within ASTM Specifications for Bituminous-Concrete Mixtures)....... 100

13. Asphalt Extraction Test Results (Bituminous-Concrete Mixtures, Controlled Dense Grading). 101

LIST OF ILLUSTRATIONS

List of Figures

Figures Page

1. Supporting Power of Bituminous Surfacing Mixtures........ 17

2. Typical Gradation Limits for 3/4 - in. Max. Size Dense-Graded Bituminous Surface Mixtures................ 28

2a. Gradation Curve for 3/4-in. Max. Size Dense-Graded Bituminous Surface Mixtures.............................. 29

3. Gradation Curves for Crusher Dust-Natural Aggregate Blends within ASTM Specifications for Bituminous-Concrete Mixtures...................................... 32

4. Details of Triaxial Cell................................ 52

5. Comparative Densities of Test Specimens vs. Percent Crusher Dust.................................. 70

6. Compressive Strength or Stability vs. Percent Crusher Dust (Bituminous-Concrete Mixtures, Controlled Dense Grading)................................ 72

7. Compressive Strength or Stability vs. Percent Crusher Dust (Sand-Asphalt Mixtures).................... 74

8. Compressive Strength or Stability vs. Percent Crusher Dust (Crusher Dust-Natural Aggregate Blends within ASTM Specifications, Bituminous-Concrete Mixtures). 76

9. Cohesion and Angle of Internal Friction vs. Percent Crusher Dust (Bitumious-Concrete Mixtures, Controlled Dense Grading)............................ 80

10. Cohesion and Angle of Internal Friction vs. Percent Crusher Dust (Sand-Asphalt Mixtures)..................... 81

11. Cohesion and Angle of Internal Friction vs. Percent Crusher Dust (Crusher Dust-Natural Aggregate Blends within ASTM Specifications, Bituminous-Concrete Mixtures). 82

12. Distribution of Asphalt and Triaxial Strength Characteristics vs. Percent Crusher Dust (Bituminous-Concrete Mixtures)......................... 84

13. Plot of Compressive Strength vs. Lateral Pressure........ 90

14. Typical Mohr's Rupture Envelope......................... 90

List of Plates

Plate Page

I. Round Natural Fine Aggregate.............................. 23

II. Crusher Dust Fine Aggregate.............................. 24

III. Quartzite Gravel Coarse Aggregate........................ 25

IV. Corps of Engineers' Compaction Mold
and Hammer with Marshall Test Specimen.................. 40

V. Marshall Compression Testing Machine.................... 41

VI. Double - Plunger Compaction Method
for Bituminous-Aggregate Mixtures....................... 48

VII. Typical Test Specimens and Unassembled
Mold (Triaxial, Modified ASTM, ASTM, and Marshall)...... 49

VIII. Unassembled Triaxial Apparatus with Test Specimen....... 55

IX. General View of Triaxial Apparatus Ready for Test
(Air Pressure Gauge and Regulator not shown)............ 57

X. ASTM Compression Test in Progress
(ASTM and Modified ASTM test specimens)................. 59

ABSTRACT

A laboratory investigation into some of the strength effects resulting from the presence of crushed-gravel fine aggregate in the bituminous mixtures is reported. The scope of this investigation was the comparison of strength test results from the Marshall Test, and "open system" triaxial test, and the ASTM compression test on ASTM and Modified ASTM test specimens. The strength properties of each mixture containing various percentages of crushed-gravel fine aggregate were evaluated from these standard tests.

The main variable used in this investigation was the percentage of crushed-gravel fine aggregate, locally called "crusher dust", in the fine aggregate portions of three types of bituminous surface mixtures: namely, a dense-graded bituminous-concrete mixture, a dense-graded sand-asphalt mixture, and bituminous-concrete mixtures consisting of crusher dust-natural aggregate blends within ASTM specifications for 3/4-inch maximum size aggregate. Round natural sand and the crusher dust provided the contrast in fine aggregate characteristics, and in order to accentuate the effects of the fine aggregate, a uniform-type quartzite gravel was used as the coarse aggregate in the bituminous-concrete mixtures. All of the bituminous-aggregate mixtures tested were hot mixtures in which an asphalt cement (85-100 penetration) was used. The asphalt content of each mixture was that determined by the Corps of Engineers' design procedure. Each mixture was tested at its respective design asphalt content.

The results of this investigation indicated appreciable increases

in mixture strength as the percentage of crusher dust in the fine aggregate was increased. This was found to be true for all the types of mixtures investigated and for all the types of laboratory tests used in this investigation. In general, percentages of crusher dust in the fine aggregate of 25 to 75 percent provided the greatest improvement in mixture strength.

Additional investigation indicated that distribution of asphalt between the coarse aggregate and fine aggregate fractions of the bituminous-concrete mixtures had an influence on the triaxial strength characteristics of these mixtures. This distribution of asphalt within these mixtures was influenced by the amount of asphalt in the mixture, which in turn was influenced by the amount of crushed-gravel fine aggregate.

It was demonstrated that the addition of crushed-gravel fine aggregate to round natural sand materially increased the strength of bituminous-concrete mixtures and sand-asphalt mixtures prepared with all round natural sand in the fine aggregate.

EFFECT OF CRUSHED-GRAVEL FINE AGGREGATE
ON THE
STRENGTH OF BITUMINOUS SURFACE MIXTURES

INTRODUCTION

Ever since the first days of modern bituminous paving construction, one of the prime interests of highway engineers has been centered around increasing the strength of bituminous surface mixtures. In this consideration, they have been aware that the shape and texture of the mineral aggregate affect the strength of the bituminous mixtures in which the aggregate is used. It has been found that mixtures containing mineral aggregate with markedly angular and rough-textured characteristics generally develop a greater strength or stability [1] than the same mixtures made with round, smooth-textured mineral aggregates. Since an increase of stability presently is greatly desired because of the development of heavier traffic loads on pavements, highway engineers have been specifying the use of crushed mineral aggregates in the coarse aggregate fraction of bituminous pavement mixtures whenever and wherever practical.

---

[1] Stability is generally defined as that property of a bituminous-aggregate mixture which permits the mix to successfully resist permanent distortions under traffic loads.

In many areas of the country where gravel sources are abundant, the strength of the local bituminous surfaces mixtures has been increased by crushing part of the round gravel used as the coarse aggregate in the mixture. This was thought to be a promising approach since crushed-gravel coarse aggregate was more angular and rough-textured than the round, natural gravel. Many highway departments have accepted this method of increasing strength in bituminous surface mixtures in specifying a certain percentage of crushed coarse aggregate in their current specifications. Sand produced by crushing stone, alone or blended with natural sands, has been used to improve mixture stability in some areas. Use of crushed sand produced from gravel is a relatively new idea.

In some sections of this country highway engineers have observed many of their asphalt pavements not meeting performace standards because of deficiencies in the local mineral aggregate incorporated into the bituminous mixes. A currently proposed remedy in some instances has been to crush the smaller-size gravels into sand size and to use the effect gained from the angularity and improved surface texture for producing satisfactory bituminous surface mixtures. There are localities where this crushed-gravel fine aggregate has been used as the entire sand fraction alone in order to render a satisfactory use of their aggregate source for bituminous surface mixtures; on the other hand, there are some localities which have found it adequate to blend a certain percentage of crushed-gravel fine aggregate with their natural plant-run sands to produce bituminous surface mixtures that will meet modern performance tests. This "sweetening" of a natural plant-run sand with a satisfactory percentage of crushed-gravel fine aggregate offers, in

many instances, a means of revitalization to aggregate sources that were depleting because they have not been able to supply the quality of aggregate that is needed for current strength requirements in bituminous surface mixtures.

Although crushed-gravel fine aggregate has been observed to increase the strength of bituminous surface mixtures, its use has been limited and there still remain questions pertaining to its limitations and feasibility when used in these mixtures.

This is an investigation, then, into the effect of crushed-gravel fine aggregate on the strength of some typical bituminous surface mixtures. The strength evaluation is based upon data obtained from three laboratory strength tests, namely; the Marshall test, a triaxial test using Mohr's theory of strength, and the ASTM Compressive Strength Test for Bituminous Mixtures (ASTM Designation: D1074-52T) as applied to Modified ASTM and ASTM test specimens. It is believed that comparisons and conclusions can be obtained from these laboratory strength tests to result in a satisfactory strength evaluation of the bituminous surface mixtures investigated.

The laboratory test data have not been correlated with data from bituminous paving mixtures containing differently shaped and textured mineral aggregates from other sources than those used in this investigation, nor have they been correlated under the conditions imposed by traffic and weather. Although the strength evaluation of the crushed-gravel fine aggregate made in this study is definitely limited in this respect, it is believed that this investigation will "pave the way" for further investigations of crusher-run gravel sands in bituminous mixtures.

REVIEW OF THE LITERATURE

The importance of using angular aggregates for producing greater strength in bituminous mixes has been reflected through many written articles. However, a great percentage of these articles have stressed the importance of angular aggregates in the coarse aggregate fraction of bituminous mixtures, and it has been only recently that a substantial amount of literature has been published on the subject of angularity of sands in the fine aggregate fraction of bituminous mixtures. The importance of angularity in the fine aggregate of bituminous surface mixtures has been realized in the past few years mainly by field experience. Research and testing programs, such as the one conducted by the Cooley Gravel Company in Denver, Colorado(10) [2] in which crushed-gravel sand was used, are few in number.

In order to have an understanding of the procedures, tests and materials used in this investigation, this review of literature will embrace some of the literature pertaining to the following topics: (a) Characteristics of Bituminous Surface Mixtures, (b) Aggregate Shape and Stability, (c) Fine Aggregate Factors Affecting Mixture Strength, (d) Corps of Engineers' Design Test, (e) Triaxial Compression Test, and (f) ASTM Compression Test.

---

[2] Numbers in parentheses refer to references listed in the List of Refernces.

Characteristics of Bituminous Surface Mixtures

The modern flexible-type pavement is a composite structure of a number of superimposed layers of bituminous and non-bituminous courses resting on the subgrade. The component parts, although interdependent, function as a whole. Each component part carries a stress imposed by traffic loads and distributes this stress to a lower component. The primary function of the combined structure is to have adequate bearing capacity for carrying all traffic loads imposed on it and to reduce the stress transmitted to the soil subgrade to a value which it is capable of supporting without excessive deformation.

The wearing surface, or bituminous surface mixture, transmits the highest stress and therefore its design must incorporate the highest strength values of the whole pavement. In order to avoid such surface failures as shoving and rutting, a correctly designed wearing course should be of sufficient thickness and stability to resist displacement by the action of traffic. Adequate strength and durability of the mineral aggregates are necessary for this purpose in addition to the ability of the bituminous binder to withstand weathering effects and hold the aggregates in place under load stresses.

The load-bearing capacity of the aggregate will depend upon its strength and upon the degree to which the particles are held in place either by interlocking or by the cementing action of the bituminous binder. Well-graded and compacted aggregate, therefore, is less dependent upon the bituminous binder for stability and, conversely, where good interlocking is lacking, either because of deficiency in grading or because of the nature of the aggregate, the bond required for stab-

ility must be provided by the bituminous material.

If the bituminous material available is deficient in cementing properties, the aggregate used with it should possess the necessary inherent stability due to its dense grading and surface characteristic. This does not mean, however, that cementitious binders are not used with dense-graded aggregates. In fact, this combination is frequently used where increased strength and resistance to moisture and oxidization of the bituminous material in service are required. Typical examples of this combination are standard sheet asphalt and hot-mixed, hot-laid bituminous concrete pavements (5,6) in which the aggregates are densely graded and the bituminous material is an asphaltic cement that, after mixing with the hot aggregate, develops cementing property at air temperature.

Aggregate Shape and Stability

The shape of mineral aggregate is difficult to define and measure. Shape is usually defined as the degree of roundness or the degree of angularity of the aggregate. Individual pieces may be observed as angular, rounded, flat and elongated, or any combination of these and other shapes. Their shape characteristics are most practically defined by the widely used method of visual examination.

Angularity is specified in highway construction by the number of fractured faces of a piece of gravel. Various state highway department specifications define a crushed-gravel aggregate as one possessing one or more appreciably crushed or fractured faces. The specifications usually require a minimum percentage of gravel to be crushed when the

gravel is used as the coarse aggregate. The minimum percentage of crushed gravel specified varies with the type of bituminous mixture in which it is incorporated, and generally the minimum percentage increases with higher types of bituminous mixtures.

Surface texture of the aggregate usually varies as the shape is changed. There is little information available regarding what part of the change of strength is due to the change in surface texture, and what part is due to the change in shape. Primarily this lack of information has been due to the absence of a desirable method for measuring surface texture and shape of the aggregate.

Paving engineers began to be concerned with aggregate shape when they observed the performance of crushed stone and round gravel in bituminous surface mixtures. The angular crushed-stone aggregates in these mixtures were seen to give more stability than round gravel aggregates in the general case. It was believed that the round gravel did not interlock as well as the angular crushed stone in these mixtures. The increased stability was believed due to the excellent interlocking qualities of the sharp, angular aggregate(22).

With the greater use of higher types of bituminous-aggregate mixtures, specific ideas began to gradually change. Thus, the idea developed that the shape of the aggregate becomes less important with higher types of bituminous mixtures. Open and one-size aggregate gradations for surface treatments and macadams definitely need angular aggregates (34). Conversely, dense-graded bituminous mixtures have been found to be quite stable, in instances, when made with round gravel(27). The stability of dense-graded bituminous mixtures was thought to be more dependent upon the amount and gradation of fine aggregate and the proportion of bituminous binder rather than on the amount of crushed aggregate particles (39).

Campen and Smith (8), using the Omaha Testing Laboratory bearing-index, and Martin and Layman (27), using the Hveem Stabilometer for the evaluation of dense-graded bituminous-aggregate mixtures, have found that angular crushed stone produces a more stable mix than round gravel. When angular crushed-stone sand was used instead of a natural river sand, they found that the stability of the mixtures was increased regardless of whether crushed-stone or uncrushed-gravel was used as the coarse aggregate fraction. This follows in line with the observation made by Herrin (19) on his work with similar types of aggregate and mixtures.

Fine Aggregate Factors Affecting Mixture Strength

The fine aggregate used in bituminous mixtures is generally called "sand" and is the fine granular material resulting from the natural disintegration of rock or the commercial crushing of gravel or stone. There are several definitions of the size of sand particles. The ASTM Committee on Soils for Engineering Purposes defines sand as being between 0.05 and 2.0 mm., 2.0 mm. being the opening of a No. 10 mesh sieve. On the other hand, numerous other sources define sand as that material passing a No. 4 or $\frac{1}{4}$ inch sieve instead of a No. 10 mesh sieve, and many contractors, engineers and designers think of sand in that sense, especially as applied to bituminous mixtures.

Generally, there are many different types of sand, each of which possesses a characteristic gradation and aggregate shape. It is often necessary that two or more of the different types of sand be blended in order to have a desirable gradation and mix-stability for bituminous mixtures.

The Barber-Greene Company, in their handbook (6), states the following definition of artificial sand:

> Artificial sand is the fine material below a No. 4 or $\frac{1}{4}$ inch in size produced when gravel or stone is crushed. Crusher screenings are often called artificial sands and are that part of crushed stone or gravel passing a No. 4 or $\frac{1}{4}$ inch screen. These screenings vary considerably as to angularity and gradation, depending upon the type of rock crushed. Most crusher screenings range in gradation from $\frac{1}{4}$ inch down to and including 0 to 6 percent passing the No. 200 mesh sieve, and they are fairly well graded, although in many cases they are deficient in the No. 40 to No. 100 mesh size.

Round and natural sands are extracted commercially from gravel pits, sand pits, or along waterways such as streams and lakes. In any case, they are deposited and worked by wind, water or ice and have been subjected to chemical disintegration. Although the sands differ among themselves (36), the factors of nature generally produce round and smooth-faced sand grains. However, the angular characteristics of natural sand are more variable as compared to an artificial sand, or a sand resulting from a crushing process.

In 1929 Kriege and Gilbert(26) began investigations on some of the salient properties of bitumen-aggregate mixtures which control their behavior in pavements. They stated:

> One factor which came up early for consideration was the effect of 10 - 15 percent of limestone fine aggregate (1/8 inch to dust) as a bitumen carrier on the structural strength of the whole mix. The results pointed in every case to marked increase in strength with the fine material present. This appeared to have a stabilizing effect not only on the asphaltic material but on a wedging action preventing the easy displacement of the coarse aggregate particles from their original position. The latter effect is apparently the more important.

Others, such as Spielman and Hughes (420), agree that sand angularity is important for strength and give the credit for high strength characteristics to compaction and a small percentage of voids present in

the mixture when angular sands are used. Skidmore (40) agrees, but further states that the subject of fine aggregate strength in bituminous mixtures divides itself into two distinct sections, fine aggregate, exclusive of filler, and filler, each requiring somewhat different treatment. He goes on to say that fillers give different results with a given sand and each should be studied separately for the type of mixture investigated. It is the opinion of many that fillers make a mix more or less workable according to the amount used, and that mixture strength is influenced not only by gradation and angularity of the sand, but by the amount and character of the mineral filler as well. Hubbard (22) states that the addition of a mineral filler to any sand will increase stability so long as it reduces voids in the aggregate.

Some paving engineers such as Skidmore (40) agree that stability of bituminous mixtures increases with the angularity of the fine aggregate; however, they further believe that inherent stability of the coarse aggregate is relatively high compared to the fine aggregate. They believe that the hardness of the individual fragment is not nearly so important a characteristic in sands as in coarse aggregates. However, others like Herrin (19) found the converse to be true. They found that regardless of the type of coarse aggregate used, the greatest change in stability was due to the properties of the fine aggregate-which varied from an angular sand to a round natural sand. Campen and Smith (8) say that satisfactory stability can be developed by replacing from 20 to 40 percent of the aggregate in a weak-sand mixture with angular sand.

W. H. Campen, in a discussion on Vokac's article (48), and investigations made by the Cooley Gravel Company of Denver (10) seem to agree that the addition of round natural sand increases workability of the mix

due to its lubricating qualities and at the same time reduces stability.

The Cooley Gravel Company (10), after conducting strength tests for comparing their local natural sand with a crushed-gravel sand in bituminous-concrete mixtures, found the following information:

> In as much as angularity of the particles is a factor in the stability of asphalt mixes, we had the Omaha Testing Lab. determine the percent of crushed particles in our crusher run. These results are found at the bottom of Page 5, [94.8%] . We belive the ability of these crushed particles to increase internal friction, the gradation of the crusher product and the fact that the fines are actually dust of fracture rather than clay or soil are the contributing factors that go to make this crusher run material superior to most of the material now used in this area. From an economic standpoint, it will be a one bin material, produced at not exceeding 3% moisture content, and no mineral filler will be required. It will make an asphalt mix that may be used for anything from a skin patch to a 2 inch deck with consistent results. We feel that it will eliminate the necessity of a seal coat often required with a coarser aggregate used in Colorado.

The properties of the fine aggregate that contribute to the stability of a bituminous mixture can be summarized as follows:

1. Grading. (6,40,19,49,24)
2. Angularity, surface texture and porosity. (35,12,40,26, 38,19,8)
3. Filler fineness, shape of grains, etc. (40,33)
4. Hardness. (40)
5. Uniformity of mixture and manufacture control. (40,6)
6. Voids in dry state. (40,42)

Corps of Engineers' Design Test

During World War II the Corps of Engineers was faced with the necessity for developing a method of bituminous mixture design and a simple readily performed stability test that could be employed reliably by those who were not specialists. The goal was field use and simple techniques.

Early work carried out in this direction consisted in a survey of existing test methods. All were abandoned for certain reasons except the Marshall Test apparatus. The test itself is simple and the apparatus is rugged and portable. The Corps of Engineers then decide to do further development work on mixture design utilizing the Marshall apparatus.

The work on the Marshall Test has been developed by the Corps of Engineers Flexible Pavement Laboratory at the U.S. Waterways Experiment Station, Vicksburg, Mississippi. At the present time the Corps of Engineers are continuing the correlation of Marshall Test data with design and field performance. McFadden and Ricketts (28) have written on the Corps of Engineers' survey on the design and field control of asphalt paving for military organizations.

The Corps of Engineers' design procedure limits aggregate gradations for the specific type of bituminous-aggregate mixture produced. One of the main purposes of the procedure is the determination of design asphalt content. Here the Corps specifies laboratory mixing procedures and methods. Specimens of a given aggregate gradation and variable asphalt contents are compacted by means of a standard hammer in a standard mold. The Corps then uses the Marshall test for determining a stability property and a deformation property, which are later correlated with void content and density of the specimens, in order to compute a design asphalt content. The Marshall Stability value has been used as a measure of the strength properties of bituminous-aggregate mixtures.

The Marshall test is a compression test that is performed on a ~~circular~~ cylindrical specimen 2½ inches high by 4 inches in diameter. The unique feature of the test is that the load is applied on the curved surface of the specimen rather than on the plane faces. The specimen is

loaded to failure by circular loading heads moving together at a constant rate of two inches per minute. The test is generally considered as a semi-confined test. Goetz (14) found the degree of confinement in the Marshall Test to be approximately equal to a lateral pressure of 10 psi. when correlated with triaxial tests.

The asphalt content selected by this method is said to be the one which would provide satisfactory performance of the mixture after compaction by traffic.

Triaxial Compression Test

The present status of triaxial testing of bitumious paving mixtures as the most rational design approach has been well summarized by McLeod (31).

The word "triaxial" is applied to a form of mechanical test under which a load is applied axially to a cylindrical specimen while a supporting pressure is maintained against its sides by a fluid. The stress-resistant properties of the material tested triaxially are derived from the relation between the testing load and the supporting pressure.

Because of the close similarity of problems involved in testing both soils and bituminous paving materials due to their similarities of plastic behavior under stress, the triaxial test is usually applied to materials belonging to the class of plastic materials rather than that of rigid-elastic materials. Soils engineers and bituminous paving engineers have used Mohr's theory of strength (23,31,46,47) for the determination of mixture strength characteristics obtained by the triaxial test.

In order to have a better understanding of the triaxial strength characteristics of bituminous mixtures, the following discussion is presented from a paper by Hveem (23):

> One property possessed by all masses of granular materials, regardless of size or shape, is some degree of internal friction which tends to resist movement or deformation of the total mass. The frictional resistance of solid particles under a given condition varies directly with the pressure to which they are subjected, is relatively independent of the speed of action and independent of the area in contact. The observation that bituminous mixtures may develop stability regardless of the variations in mineral aggregate is entirely compatible with this principle.
>
> From a consideration of this one quality of stability, it can now be concluded that bituminous mixtures possess only two fundamental properties which combine to produce stability of the mixture. One property is frictional resistance between the solid particles of mineral aggregate, and the other is frictional resistance in the films of bituminous binder. Liquid friction contributed by the asphalt may be variously designated as viscosity, cohesion, or tensile strength.
>
> Unfortunately, these two basic factors, which will henceforth be called simply friction and cohesion, do not contribute to stability either in equal degree or in kind, and it becomes necessary to decide whether to aim at increasing the friction or the cohesion or a combination of both, when designing the bituminous pavement.
>
> Hveem goes on to say:
>
> High frictional resistance is obtained by selecting aggregates having a sandpaper-like surface texture, and with the quantity of asphalt maintained definitely below the total void volume. The percentage of voids which may be filled with asphalt is positively a variable and differs for each type of grading and asphalt used. In other words, knowing only the voids in a mixture and with no other information it is not possible to determine the quantity of asphalt binder which will give the best results.
>
> High cohesional strength can be obtained by use of low penetration asphalts and by increasing the quantity of fine sand and filler dust. Sheet asphalt mixtures, for example, develop very much higher cohesion than is the case with asphalt concrete. Asphalt concrete surface mixtures containing filler dust show much higher tensile strength than do base and leveling course mixtures without filler.
>
> In order to resist weather action, a relatively rich mix is desirable. The heavier the film coating on the particles of aggregate, the greater will be the resistance to aging and deterioration of the asphalt. However, if this condition is allowed to dominate the de-

sign, there is considerable danger that an unstable mix will be developed. Resistance to abrasion, raveling, and impact also increases a s the quantity of asphalt is increased. But unfortunately while we are improving the mixture to increase cohesion and "malleability" which are in themselves desirable, increasing the thickness of lubricating films beyond a certain point will simultaneously reduce the friction on which stability so largely depends.

Therefore it can be concluded that, although cohesion and internal friction are independent properties and each affects the stability of a bituminous-aggregate mixture, over-emphasis on either cohesion or internal friction in mixture design can result in a mixture of low durability or stability.

Techniques (4,9,15,18,31,41,23) used to perform the triaxial test as found in the literature are many. However, each method has the same end, the determination of c, the unit cohesion, and ϕ, the angle of internal friction of the material under consideration.

In the open system test, such as was used in this investigation, several cylindrical test specimens, usually two or more, are tested at different confining pressures. The Mohr circle[3] for each confining pressure and the accompanying compressive stress at failure is plotted and the envelope of the circles is drawn. This envelope, called the "Mohr Envelope of Rupture", is the graph of the equation $s=c+p \tan \phi$, where:

s = shearing strength in psi.
c = unit cohesion in psi.
p = normal stress in psi.
ϕ = angle of internal friction in degrees.

The inclination of the Mohr envelope with the abcissa is defined as ϕ, and its intercept on the ordinate is defined as c.

---

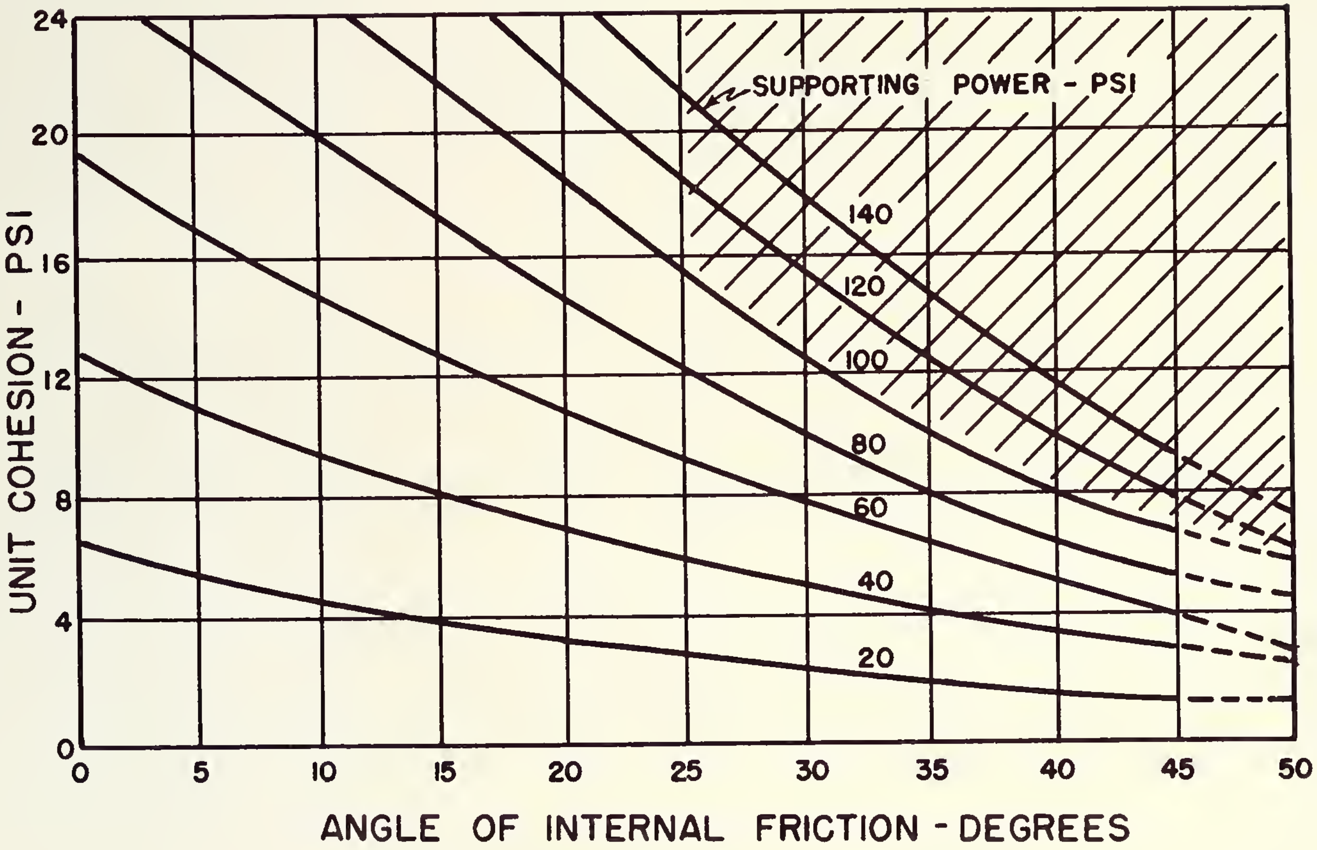
[3] A brief review of the Mohr circle and theory of failure relationships is included in Appendix A.

In bituminous mixes, there is some relationship between compressive shearing strength and tensile strength but it is not correctly represented by the Mohr envelope (4).

In applying the Mohr Theory, the envelope is frequently assumed to be a straight line. This applies rigorously, however, only to "linear-plastic" materials or materials whose shear resisting properties do not change with progressive deformation, and in specimens of dimensions which will preclude interference from end effects. In bituminous-aggregate mixtures the envelope is usually found to be curved; however, as the height-diameter ratio of the test specimen increases, the apparent friction becomes less and the envelope straighter. Taking into consideration that specimen diameter should be at least 4 times the largest aggregate size in the mixture in order to minimize effects of non-homogeniety, and with a height-diameter ratio of 3, it is possible to get an envelope approximating a straight line. A specimen height approximating eight inches with bituminous-concrete mixtures is usually employed in order to eliminate the effects of interference of shear cones and friction against the loading heads (41). Smith and the Asphalt Institute recommend a specimen four inches in diameter and eight inches high for mixtures with 3/4-inch top size.

Figure 1 shows Smith's adaptions of triaxial strength data to applications in flexible pavement design. It is an attempt to correlate laboratory stability, as determined from a triaxial test, with field stability. Smith found the 100 psi. supporting curve to be a boundary between satisfactory and unsatisfactory field performance for primary roads. With further correlation, Smith found that mixtures having an angle of internal friction less than 25 degrees became unstable under traffic conditions. These two criteria have delineated the region of "satisfactory mixtures"

SUPPORTING POWER OF BITUMINOUS SURFACING MIXES



NOTE:
REGION OF SATISFACTORY MIXES INDICATED BY SHADED AREA

COMPOSITION OF CHARTS AFTER SMITH (41)

FIGURE 1

shown in Figure 1. Smith also proposed ~~to~~ enlarging the region of satisfactory mixes for lower types of bituminous construction.

From a summary of the existing literature, it can be concluded that the elements resisting failure of a specimen loaded vertically in a triaxial compression test are:

1. The lateral supporting pressure.
2. The internal cohesive properties of the mix.
3. The confining stresses resulting from friction against the testing head.
4. The internal friction of the material.

ASTM Compression Test

In 1936, early experimental work on compression testing of asphalt paving mixtures was being undertaken by Vokac (48,49). He offered data to show that the compression test measures physical characteristics such as compressive strength, elastic limit, modulus of elasticity, and resistance to flow after compressive strength has been exceeded.

Following the preliminary work Vokac gave considerable attention to developing a correlation between data obtained in the laboratory by means of the compression test and the behavior of the mixtures tested as observed in surfaces under actual field conditions. Although several other methods of test were investigated, the correlation of the data indicated that the compression test was more sensitive to the factors affecting service behavior than other tests used (48).

About 1950 the American Society for Testing Materials adopted the compression test as a tentative standard for testing bituminous-aggregate mixtures (2). The test method specifies height-diameter ratio for test

specimens, mixing and compaction procedures, and strength testing procedures.

The ASTM Compression test consists of axially loading a cyclindrical specimen of standard dimensions, four inches in diameter and four inches high, at a constant rate of 0.2 inches per minute. A test temperature of 77° F. is specified with some tolerance. Although the specimen is unsupported laterally, most paving technologists agree that the test is not an unconfined test. They agree that frictional resistance between the testing head and specimen cause a certain amount of restraint.

Some investigators, such as Smith (41), believe that compressive tests which do not involve any lateral support, or restraint, and which are influenced predominantly by the cohesive properties of the mix, tend to yield pavements on the rich side when they are used to establish asphalt content. However, compression tests as a rule are employed to determine the highest load sustained by the material (33), or as "Index of Stability" as utilized by the ASTM, and to provide for field correlation.

Housel (20), in a section of his paper entitled "The Function of Mechanical Tests", gives the following discussion on compression tests:

> As with other materials, tests can be classified as those made by the application of compressive loads, those made by shearing loads, and those made by tensile loads.
>
> Fundamentally, however, there is no such thing as a compressive test except in the yield of volume compressibility. The compression test as ordinarily used are simple methods of applying shear or flow tests, the material always flowing in this manner only.
>
> In considering the practical application of tests, it is necessary first of all to consider their relation to the manner in which loads are applied in practice. Under traffic the load is always "compressive" in a non-elastic material. That is, if the material moves, it moves by shear or flow. For evaluating resistance to such stresses, shear tests, either those usually so termed, or indirectly applied as by "compression" tests, are obviously called for. The compression test has a certain appeal here from its apparent likeness to the

condition of loading on the road. This likeness, however, is not all complete, for the following reasons:

(a) Under road conditions the loaded prism is subject to side pressure from the adjoining material.

(b) The normal test method involves pressure between rigid surfaces. Ordinarily road bases exhibit some resilient resistance, or somtimes move under load by consolidation or settlement of underlying layers, while the tire through which the load is applied causes peculiar stress distributions on the loaded area which are unlike those under a rigid plate.

Housel then states the following compression test advantages:

1. Material is free to form its own flow lines by the principle of least resistance.
2. Constant results, providing bituminous specimens have a height/diameter ratio of 2 or over.

.... and the following disadvantages:

The standard compression test is not analytic. It will show how much load a specimen will carry under given conditions, but it will not show why it will carry it. It will yield such information only through a number of tests under rather elaborate variation of conditions.

MATERIALS

The crusher-run sand produced by crushing gravel that was used in this investigation was sharp, angular, and rough-textured. The natural sand used in this investigation was a rounded material. These two locally available sands were selected because of their contrasting angularity and surface texture characteristics. In order to study more specifically the role of the fine aggregate fraction in bituminous-concrete mixtures, the type of coarse aggregate selected was uniform in shape, texture and physical makeup.

A detailed description of these aggregates as well as identifying test values on the bituminous binder are presented in the two following sections.

Mineral Aggregate

The mineral aggregates selected for use in this investigation were obtained from commercial aggregate plants and their physical characteristics were not altered in the laboratory except for gradation. During one phase of this investigation the fine aggregate (passing a No. 4 sieve) was separated into size ranges and reblended to establish a selected laboratory-controlled gradation.

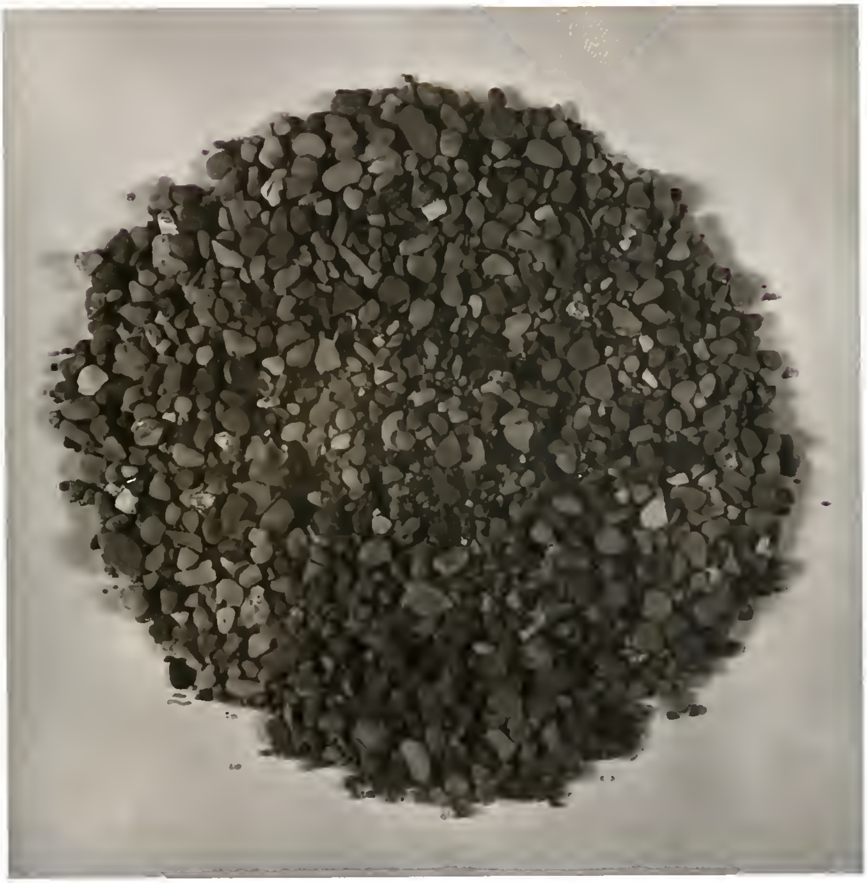
The natural sand consisted of relatively round, smooth, local materials obtained from the Western Indiana Gravel Company, Lafayette, Indiana. The natural sand components consisted of a commercial sand meeting the specifications of Indiana No. 17 sand for bituminous paving mixtures, and a fine sand obtained from the washings being discharged in the plant's fine aggregate processing unit. The fine sand was used

to supplement the smaller sizes of the Indiana No. 17 sand in order that the size amounts would be sufficient to meet the laboratory-controlled dense-gradation.

The other sand used in this investigation was a commercial crushed-gravel sand obtained from the Raymond Street Plant of the American Aggregates Corporation, Indianapolis, Indiana. This sand was selected because it represented a typical crusher-run product used locally. It was observed to be sharply angular and rough-textured. This crusher-run sand is referred to locally as "crusher dust" and has been successfully used by the City of Indianapolis for a number of years in bituminous surfacing mixtures. Its main use has been as a blending material with a local natural sand such as Indiana No. 17 sand. The crusher dust is a fine aggregate product resulting from the crushing of a 3/8-inch gravel by a commercial 48-inch Nordberg crusher.

A sample of each sand (predominantly large sizes for picture observation) showing aggregate shape characteristics is shown in Plates I and II, respectively.

The type of coarse aggregate selected was a uniform quartzite gravel from White Marsh, Maryland. This gravel was sent to Purdue University for use in this investigation by the National Sand and Gravel Association Laboratory at the University of Maryland. Visual inspection showed this gravel to be predominantly round in shape and smooth-textured. A sample of this gravel is shown in Plate III.

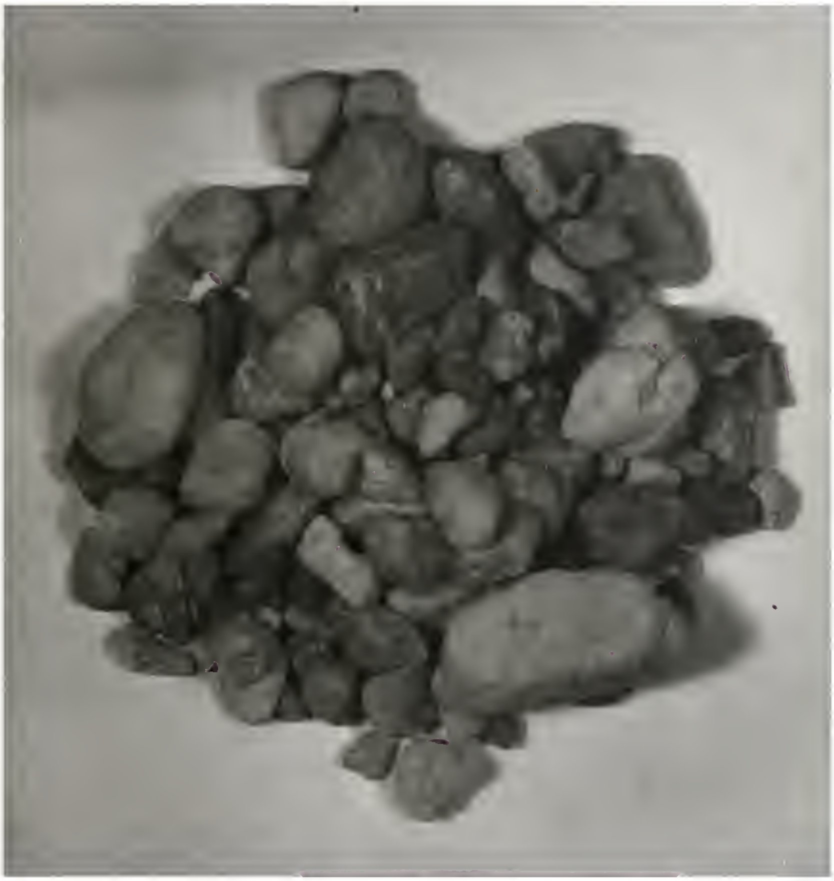


ROUND NATURAL FINE AGGREGATE

Plate I

CRUSHER DUST FINE AGGREGATE

Plate II



QUARTZITE GRAVEL COARSE AGGREGATE

Plate III

The specific gravity and the absorption values of these mineral aggregates were obtained by following procedures specified in ASTM Designations C127-42 and C128-42. These test results are shown in Table 1.

TABLE 1.

SPECIFIC GRAVITY AND ABSORPTION OF AGGREGATE

Aggregate	Apparent Sp. Gr.	Bulk Dry Sp. Gr.	%Absorption
Quartzite Gravel	2.64	2.63	0.28
Natural Sand	2.69	2.54	2.04
Crusher Dust	2.77	2.61	2.42

Since the first phase of this investigation could not embrace all types of bituminous surface mixtures because of the time factor involved, one dense-graded bituminous-concrete mixture and one dense-graded sand-asphalt mixture was selected.

The dense-graded bituminous-concrete mixture was selected on the basis that it represented a gradation within the limits of several well-known specifications, namely: Indiana AH Type "A" surface mixtures, Corps of Engineers' dense-graded asphaltic-concrete surface mixtures, the ASTM specification limits for bituminous-concrete mixtures, and near the lower limit of the Asphalt Institute's gradation limits for this type of mixture. These gradations are shown in Figure 2. The specific gradation selected was the lower limit of the Corps of Engineers' gradation for asphaltic-concrete with 3/4- in. maximum size aggregate (11) and is shown in Figure 2a.

Since it was desired to investigate the sand fraction alone, a sand-asphalt mixture was selected with a gradation identical to that of the fine aggregate fraction used in the dense-graded bituminous-concrete mixtures. The material passing a No. 200 sieve from the crusher dust was used in these mixtures as mineral filler.

Table 2 gives the laboratory-controlled sieve analyses for the dense-graded bituminous-concrete and sand-asphalt mixtures.

To study the application of blending a crusher-run sand with a natural sand from the commercial viewpoint, the Indiana No. 17 sand from the Western Indiana Gravel Company in Lafayette was blended, as received,with the plant-run crusher dust, as received, from the Raymond Street Plant of the American Aggregates Corporation in Indianapolis. The gradation of each sand from laboratory sieve analyses of representative samples is shown in Table 3. Using 48 percent fine aggregate and through blending the crusher dust with the Indiana No. 17 sand in: 100 - 0, 75 - 25, 50 - 50, and 25 - 75 percentages, the resulting gradation was within the ASTM Specifications for Hot-Mixed, Hot-Laid Asphaltic Concrete for Base and Surface Courses (ASTM Designation: D947-54T). These gradings are shown in Figure 3.

The uniform-type quartzite gravel from White Marsh, Maryland, was used as the coarse aggregate. Its gradation was held constant and is represented with the crusher dust and Indiana No. 17 plant-run sands in Figure 3.

The overall bituminous-concrete gradation of each fine aggregate blend is given in Table 4.

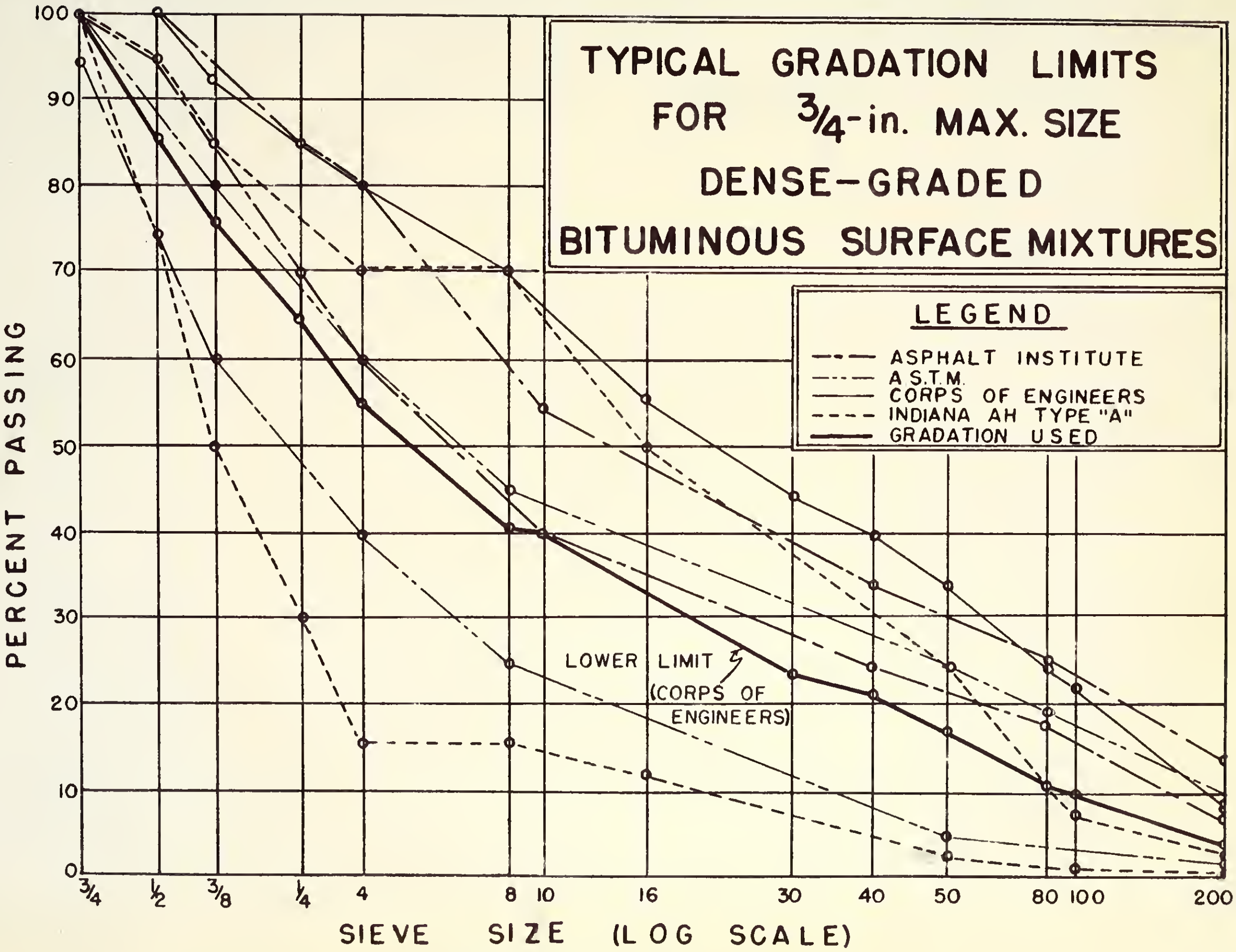

TYPICAL GRADATION LIMITS
FOR 3/4-in. MAX. SIZE
DENSE-GRADED
BITUMINOUS SURFACE MIXTURES
LEGEND
ASPHALT INSTITUTE
A.S.T.M.
CORPS OF ENGINEERS
INDIANA AH TYPE "A"
GRADATION USED
LOWER LIMIT
(CORPS OF ENGINEERS)
PERCENT PASSING
100
90
80
70
60
50
40
30
20
10
0
3/4
1/2
3/8
1/4
4
8
10
16
30
40
50
80
100
200
SIEVE SIZE (LOG SCALE)

FIGURE 2

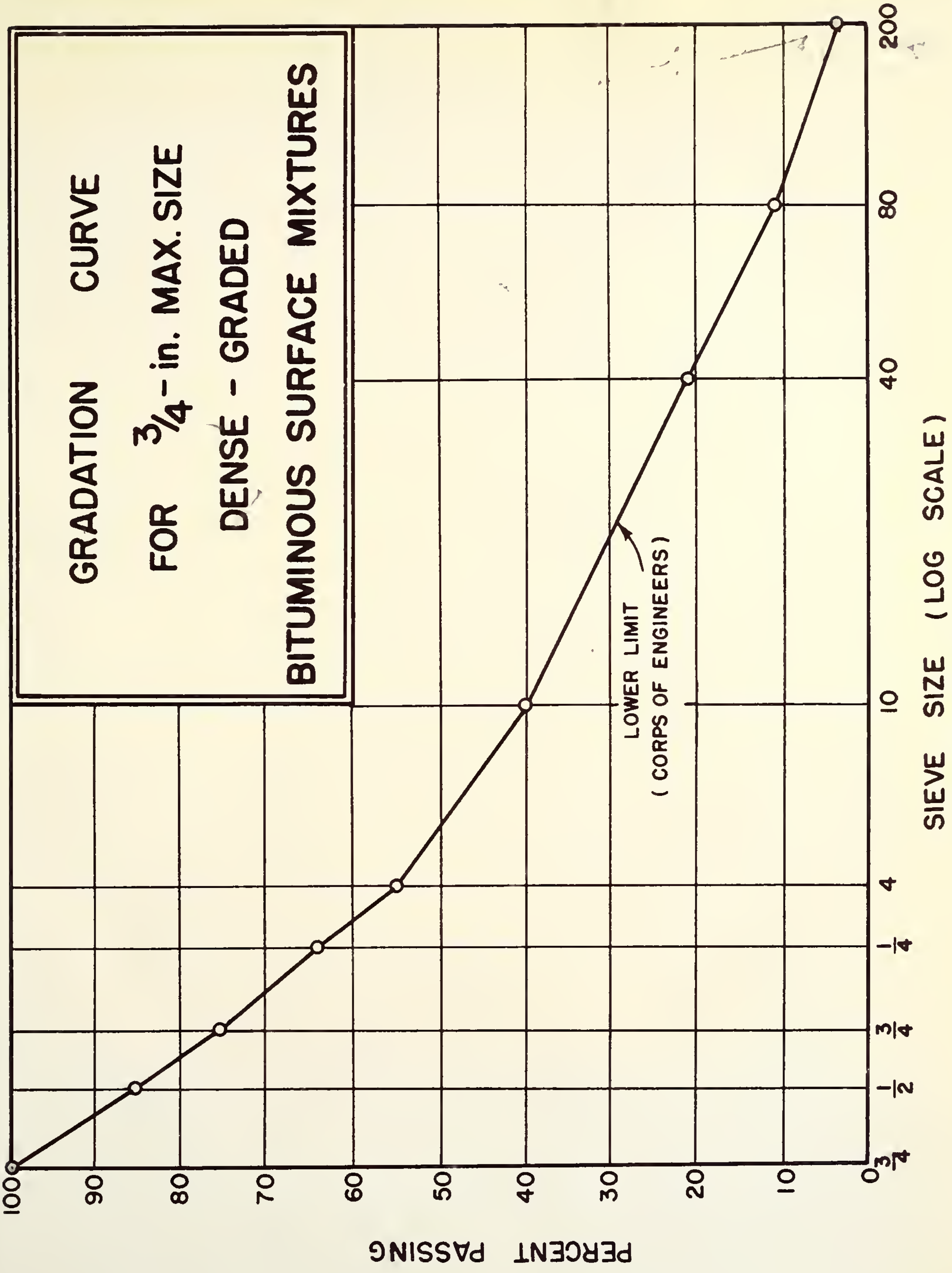

GRADATION CURVE
FOR 3/4-in. MAX. SIZE
DENSE - GRADED
BITUMINOUS SURFACE MIXTURES
LOWER LIMIT
(CORPS OF ENGINEERS)
PERCENT PASSING
100
90
80
70
60
50
40
30
20
10
0
SIEVE SIZE (LOG SCALE)
3/4
1/2
3/4
1/4
4
10
40
80
200

FIGURE 2a

TABLE 2

SIEVE ANALYSIS OF CONTROLLED DENSE-GRADED BITUMINOUS-CONCRETE and SAND-ASPHALT MIXTURES

(Percent by Weight)

MATERIAL	SIEVE		GRADING	
	Passing	Retained	Bit. Conc.	Sand Asph.
Coarse Aggregate	-	3/4"	0	0
	3/4"	1/2"	14	0
	1/2"	3/8"	11	0
	3/8"	1/4"	10	0
	1/4"	#4	10	0
Fine Aggregate	#4	#10	15	27
	#10	#40	18	33
	#40	#80	10	18
	#80	#200	8	15
Filler	#200	-	4	7

TABLE 3

SIEVE ANALYSES OF CRUSHER DUST AND INDIANA NO. 17 SAND

(Percent by Weight)

PASSING	RETAINED	CRUSHER DUST	INDIANA NO. 17 SAND
3/8"	1/4"	0.2	0
1/4"	#4	2.6	0
#4	#10	28.5	1.0
#10	#40	38.1	80.5
#40	#80	10.2	15.5
#80	#200	3.1	2.3
#200	-	17.3	0.7

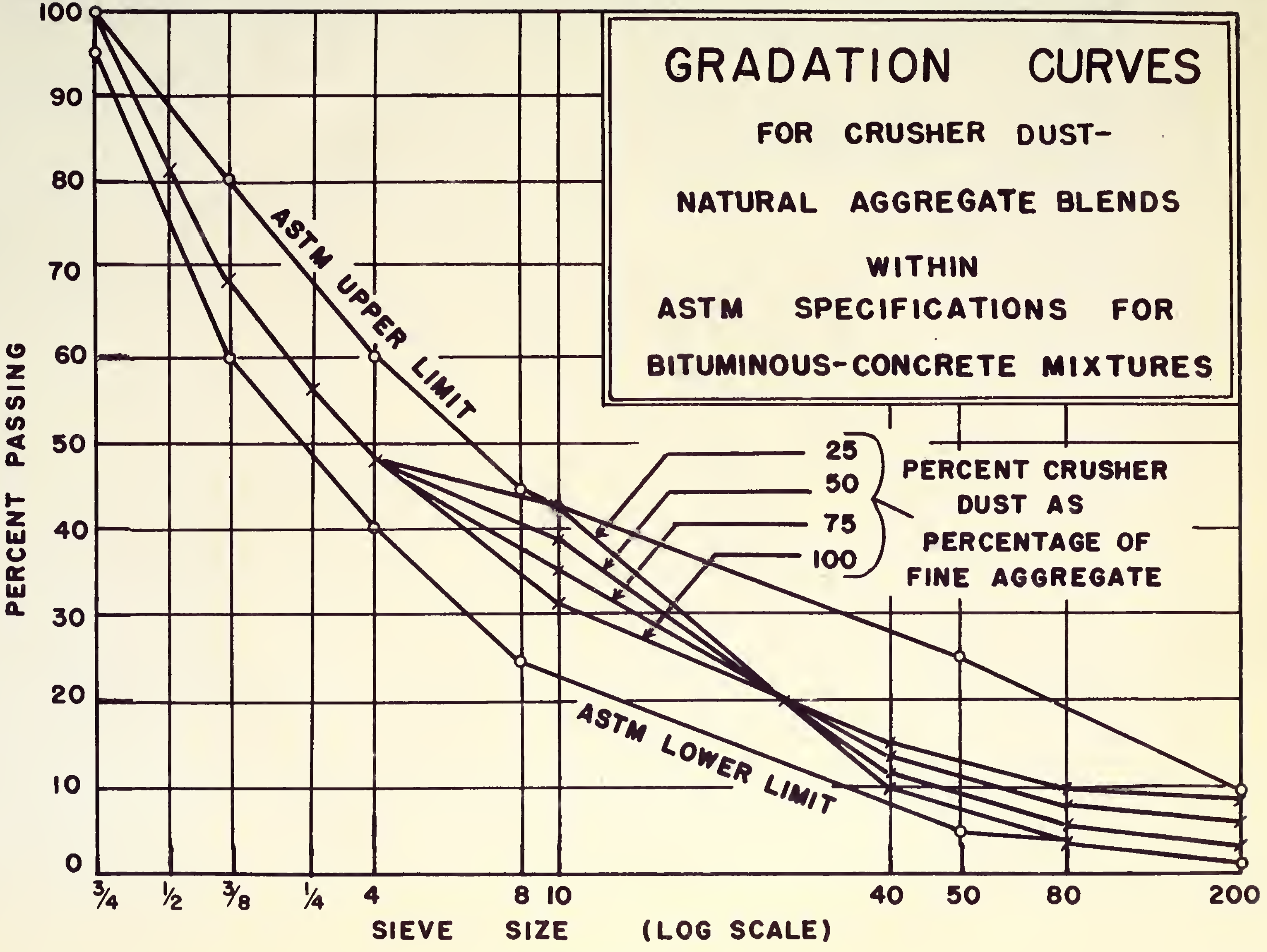

GRADATION CURVES
FOR CRUSHER DUST-
NATURAL AGGREGATE BLENDS
WITHIN
ASTM SPECIFICATIONS FOR
BITUMINOUS-CONCRETE MIXTURES
PERCENT PASSING
100
90
80
70
60
50
40
30
20
10
0
3/4
1/2
3/8
1/4
4
8
10
40
50
80
200
SIEVE SIZE (LOG SCALE)
ASTM UPPER LIMIT
ASTM LOWER LIMIT
25
50
75
100
PERCENT CRUSHER DUST AS PERCENTAGE OF FINE AGGREGATE

FIGURE 3

TABLE 4

GRADATIONS OF GRAVEL AND CRUSHER DUST - INDIANA NO. 17 SAND BLENDS
WITHIN
ASTM SPECIFICATIONS FOR BITUMINOUS-CONCRETE MIXTURES

				SIEVE SIZE						
MATERIAL	Pass Ret.	3/4 1/2	1/2 3/8	3/8 1/4	1/4 4	4 10	10 40	40 80	80 200	200 -
Percent Gravel Coarse Aggregate		34.6	26.9	23.1	15.4	-	-	-	-	-
Percent Crusher Dust		-	-	0.2	2.6	28.5	38.1	10.2	3.1	17.3
Percent Indiana No. 17 Sand		-	-	-	-	1.0	80.5	15.5	2.3	0.7
PERCENT PASS		3/4	1/2	3/8	1/4	4	10	40	80	200
25% - Crusher Dust 75% - Ind. No.17		100	82.0	68.0	56.0	48.0	44.2	10.6	3.8	2.3
50% - Crusher Dust 50% - Ind. No. 17		100	82.0	68.0	56.0	47.5	40.4	12.0	5.8	4.3
75% - Crusher Dust 25% - Ind. No. 17		100	82.0	68.0	56.0	47.0	36.6	13.2	7.7	6.3
100% - Crusher Dust		100	82.0	68.0	56.0	46.5	32.8	14.5	9.6	8.3

Bituminous Binder

Only one type of asphaltic cement was used throughout this investigation. It was an ASTM Penetration Grade 85-100 asphaltic paving cement obtained from the Standard Oil Company of Indiana. Various standard ASTM tests were performed in the laboratory on this asphaltic paving cement. The following are the test results:

Penetration . . . . (77° F., 100 g., 5 sec.)	91
Ductility . . . . (5 cm/sec., 77° F.) cms.	150+
Specific Gravity . . . . (77° F.)	1.021
Solubility in CCl_4, %	99.9+

APPARATUS and PROCEDURE

The apparatus and procedure used in this investigation is discussed under five general headings. These are:

1. Preparation of the aggregate,
2. The Corps of Engineers' Design Procedure for determining asphalt content,
3. Preparation of the test specimens,
4. Testing the specimens, and
5. Extraction tests for determining asphalt distribution.

The apparatus is enumerated along with the appropriate procedure.

Preparation of the Aggregate

The apparatus used in processing the aggregate preparatory to the forming of test specimens is as follows: "Gilson" mechanical sieving machine, Tyler "Ro-tap" testing sieve shaker, U. S. Standard sieves, Nos. 4, 10, 40, 80, and 200, and a torsion balance.

The mineral aggregate as received was divided into coarse and fine aggregate fractions. The coarse aggregate (quartzite gravel) was shipped to Purdue University in burlap bags containing the pre-graded sizes. However, the fine aggregates were received in bulk quantities from the plants. In the first phase of preparation, each of the two types of sand were air-dried and sieved into the respective sieve fractions and recombined in the desired proportions. The second phase of preparation consisted of air-drying the sands, sieve analyses, and batching the whole portion of each sand fraction.

The coarse aggregates were pre-graded to the desired aggregate fractions: 3/4 inch to 1/2 inch, 1/2 inch to 3/8 inch, 3/8 inch to 1/4

inch, and 1/4 inch to No. 4. In some instances pieces of aggregate were removed in order to establish a more uniform coarse aggregate fraction.

In the first preparation phase the fine aggregates were sieved using a "Gilson" mechanical testing machine, or in the case of the smaller aggregate sizes in the sand fraction, a Tyler "Ro-tap" testing sieve shaker was used. The sieves used were U.S. Standard sieves, sizes Nos. 4, 10, 40, 80, and 200. It should be noted again that the crusher-dust material passing a No. 200 sieve was used in both the crusher-dust and natural-sand fine aggregate fractions. The sieved aggregate was stored and accumulated for future use.

In the second preparation phase which consisted of blending plant-run sands, the crusher dust and Indiana No. 17 sand were air-dried in shallow flat pans. Following the drying period, laboratory sieve analysis obtained from several tests on each sand was used to establish the required limitations of blending within the ASTM specification limits. Table 3 gives the average sieve analysis of the crusher dust and Indiana No. 17 sand, as received from the plants.

Prior to forming the test specimens, the coarse and fine aggregates were combined in a manner which incorporated into the aggregate mixes various percentages of crushed-gravel in the fine aggregate. The percentages used were as follows:

1. 100% crusher dust, 0% natural sand.
2. 75% " , 25% " " .
3. 50% " , 50% " " .
4. 25% " , 75% " " .

(continued next page)

*5. 0% crusher dust, 100% natural sand.

In the first preparatory phase, the specific dense gradation was achieved utilizing laboratory-controlled blending by weight fractions of the various aggregate sizes. The pre-graded coarse aggregate and the sieved fine aggregate were combined by weight in the proportions given in Table 2 and shown graphically in Figure 2a. The sand fraction of the bituminous-concrete mixtures and the sand-asphalt mixtures varied, then, with the specified percentages of crusher dust and natural sand.

The second preparatory phase untilized the blending of plant-run sands, namely, the crusher dust and Indiana No. 17 sand, in bituminous-concrete mixtures. The pre-graded coarse aggregate and representative samples of crusher dust and Indiana No. 17 sand were combined by weight in the correct proportions. Using 52 percent of gravel by weight of aggregate, the coarse aggregate was combined in the proportions as given in Table 4. The plant-run crusher dust and Indiana No. 17 sand were blended, as received, in the specified percentages to establish the remaining 48 percent of sand by weight of aggregate. These sand blends produce gradations as given in Table 4. The over-all gradations of the plant-run sands in the bituminous-concrete mixtures are shown in Figure 3.

---

* This blend was used only in the Corps of Engineers' dense-type gradation for bituminous-concrete and sand-asphal mixtures. For plant-run blends of 0% crusher dust and 100% Indiana No. 17 sand, the overall bituminous-concrete gradation using these percentages would extend beyond the ASTM limits.

The Corps of Engineers' Design Procedure for Determining Asphalt Content

The asphalt content used in the dense-graded bituminous-concrete and sand-asphalt mixtures was obtained by using the Corps of Engineers' design procedure (50). Likewise, the Corps of Engineers' design procedure also established the design asphalt content for the bituminous-concrete mixtures produced from the blends of coarse aggregate, plant-run crusher dust and Indiana No. 17 sand. Each mixture was prepared with its established design asphalt content, and although the asphalt content for each mixture differed, the asphalt content was not considered a main variable in the strength evaluation of these mixtures.

The Corps of Engineers' design procedure was used in this investigation for the following reasons:

1. It is a widely used and successful method for determining the design asphalt contents of both bituminous-concrete and sand-asphalt mixtures.

2. In one phase of this investigation the specific gradation used was the lower limit of the Corps of Engineers' specifications. Since this gradation was within the Corps of Engineers' specifications for these mixtures, the Corps of Engineers' design procedure was reliable and accurate.
   This procedure was also used in the plant-run bituminous-concrete mixtures, although several of the gradations extended outside the lower limit of the Corps of Engineers' specifications.

3. The Marshall Test, a part of the Corps of Engineers' design procedure, gave a Stability value which could be used for comparison with the strength values obtained from other tests.

The design procedure was performed under standard conditions and with standard apparatus (50). Approximately 2500 g. of aggregate was batched by weighing individual fractions according to the prescribed gradation of the fine aggregate and then was heated in an oven to 325° F. The 85 - 100 pen. asphaltic cement was heated in the same oven to 260° F. and added to the hot aggregate in a mixing bowl on a percent by weight

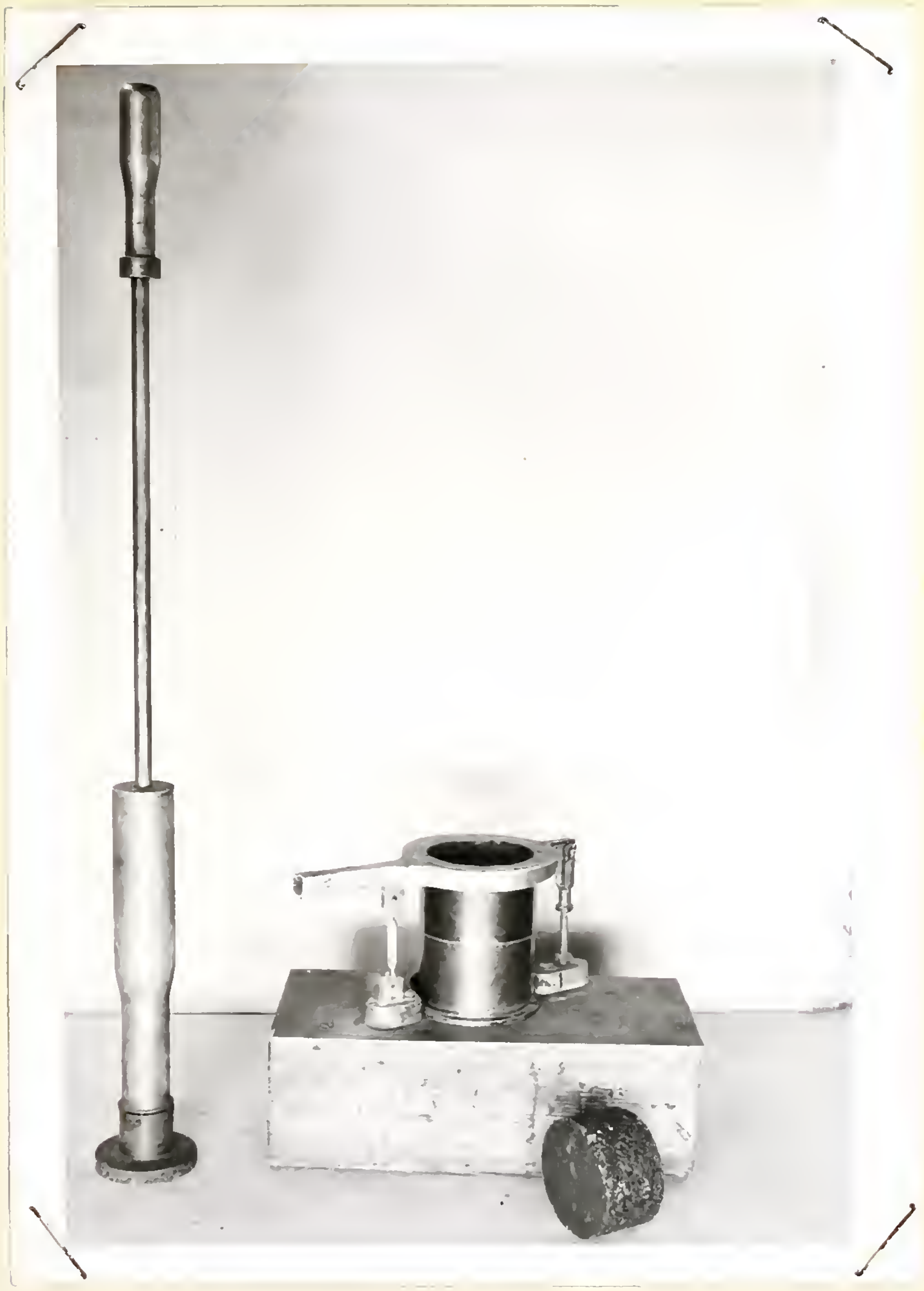
basis of the aggregate. After mixing for two minutes with an electric mixer, the bituminous-aggregate mixture was ready for molding.

The mixture was then transferred to a pan and divided into two equal portions. Each half was placed in a clean compaction mold heated to a temperature of approximately 250° F. After the mixture had been placed in the mold, the mold assembly was placed on the compaction base and a standard compaction of 50 blows from an oven-heated hammer (10 lb. weight falling through a distance of 18 in.) was applied by hand. After this operation, the base plate and collar were removed and the mold reversed and reassembled so that the base plate was adjacent to the original top of the specimen. Fifty blows of the compaction hammer were applied to this face of the specimen. The base plate and collar were removed and the mold and specimens were immersed in cool water for approximately two minutes. The test specimen was then extracted and placed on a smooth, level surface until ready for testing. The height of the specimens were 2-1/2 inches, plus or minus 1/8 inch, and the diameter was 4 inches. The compaction mold, hammer, and test specimen are shown in Plate IV.

The specific gravity of each test specimen was determined by water displacement.

Four groups of duplicate test specimens were made to determine the design asphalt content for each bituminous-aggregate mixture. Each group of test specimens varied in asphalt content in 1.0 to 0.5 percent increments below and above the estimated design percentage.

Test specimens were tested for Marshall Stability and Flow values a few hours after preparation. In performing this test each test specimen was placed in a water bath at a temperature of 140° F., plus



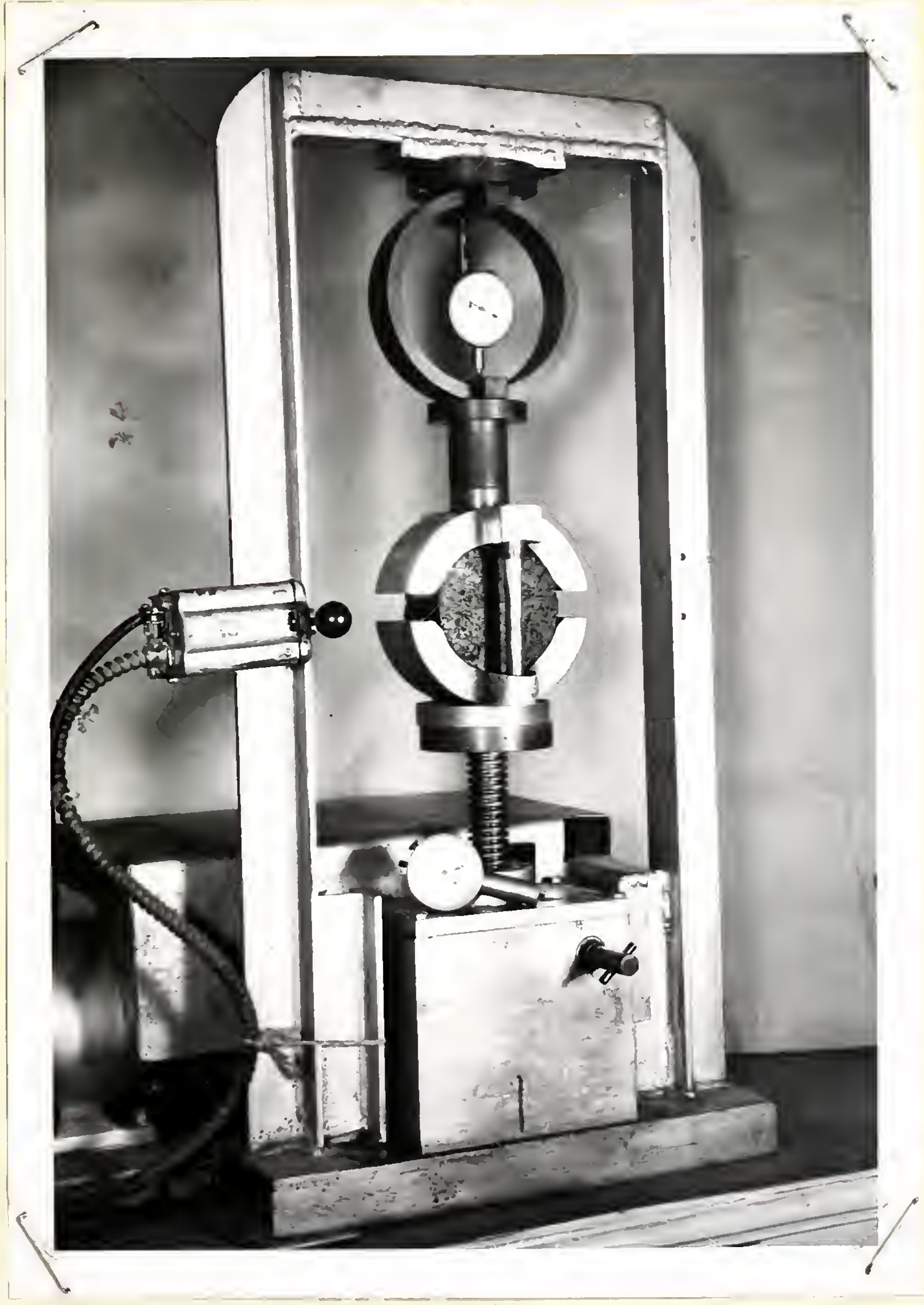
CORPS OF ENGINEERS'

COMPACTION MOLD AND HAMMER

with

MARSHALL TEST SPECIMEN

Plate IV



MARSHALL COMPRESSION TESTING

MACHINE

Plate V

or minus 1° F., for a period of at least 20 minutes. After this period of time in the water bath the test specimens were ready for the Marshall Test procedure.

The Marshall Test procedure consisted of placing the test specimens between the lower and upper curved sections of the breaking head, and the complete assembly was then placed in testing position in the machine. A flow meter was placed on one of the guide rods and lateral deformation was applied in such a manner that the lower jack head moved upwards at the rate of two inches per minute.

The hand pressure on the flow gauge was released instantly at the time the specimen indicated a maximum load value from the load dial. The Marshall Stability and Flow values were read on the load dial and flow gauge, respectively, at the time the load dial registered maximum load and began to recede towards zero. The Marshall Stability was determined in pounds of maximum load sustained by the specimen, and the Marshall Flow was determined in 1/100 ths. inches of specimen deformation. To prevent excessive cooling of the test specimen the entire testing operation was performed in 30 seconds or less.

Plate V shows the compression testing machine used for the Marshall Test. It is basically the one which is specified by the Corps of Engineers.

More detailed information concerning the Marshall Test equipment is contained in Technical Memorandum 3-254 published by the Department of the Army, Corps of Engineers, Mississippi River Commission.

Preparation of the Test Specimens

The following apparatus was used in the preparation of the triaxial, ASTM and Modified ASTM test specimens: Peerless gas oven with oven heat control, assembled compaction mold, modified Hobart electric mixer with flat-bottom mixing bowl and blade, beam balance, 3/4 inch round steel bar, and Riehle compression testing machine.

Prior to the actual molding, the asphalt and the molding equipment were prepared for use. Bulk asphalt was received in the laboratory in five gallon cans, and the desired amount was removed by cutting with a hot metal blade. The specific amount of asphalt needed for one specimen was removed from the container of asphalt and placed in a single pan. Approximately 50 additional grams of asphalt were placed into each pan to compensate for the asphalt that would adhere to the sides of the pan.

The heavy, steel 4-inch diameter compaction mold pictured in Plates VI and VII first was cleaned. The inside walls of the mold and the cylindrical surfaces of the loading pistons were coated with a light crankcase oil. The mold was then assembled by use of the alignment pins, and the lower piston held in place by a long pin. Mr. J.F. McLaughlin (29) gives a detailed description of this compaction mold.

The detailed procedure for preparation of the test specimen, after the aggregate, asphalt, and equipment were prepared, follows: (Parts of this procedure have been taken from Herrin (19))

"1. Two pans of aggregate, each containing one half the aggregate needed to form one specimen, were placed with an armored thermometer in the hot oven (oven regulator was set at 450° F.).

"2. When the temperature of the aggregate was approximately 225° F., the pan of asphalt with another armored thermometer was placed on the top shelf of the oven. At the same time the assembled compaction mold with the upper piston, a spoon, a flat pan, the brass mixing bowl, and mixing blade were placed on the next to the top shelf.

"3. All equipment and materials were heated until the temperature of the aggregate was 300 ± 10° F. and the asphalt was 275 ± 10° F. An attempt was made to have the asphalt and aggregate reach the required temperature at the same time. The asphalt was not allowed to be overheated, since its characteristics would have been changed.

"4. Just before the temperature of the materials reached the required degree, the mixing bowl was placed on the balance and the beam balance was tared. The aggregate from one pan was transferred to the bowl and weighed to the nearest gram.

"5. The amount of asphalt to be added to this aggregate was computed by multiplying the weight of the aggregate in the bowl by the percentage of asphalt the specimen was to contain. This weight was added to the beam and hot asphalt was poured into the bowl until the beam was balanced.

"6. The asphalt was returned to the oven to regain the desired temperature, and the mixing blade was removed and placed in position on the mixer.

"7. The mixing bowl, containing asphalt and aggregate, was placed in the mixer and the ingredients of the bowl were mixed at low speed for two minutes as measured by a stop watch. This mixer was a Hobart mixer, modified by providing a side scraper, a flat mixing blade and a

flat-bottom mixing bowl. (A detailed description of this mixer can be found in Reference 37.)

"8. During the mixing operation the flat pan and spoon were removed from the oven. As soon as the mixing was completed, the hot bituminous-aggregate mixture was dumped into this flat pan. To prevent this half of the material, needed for one sample, from getting cold during the mixing of the other portion, the pan and mixture were placed on the bottom shelf of the oven and the door left open.

"9. Since the bowl usually contained a small amount of the previous mixture, a new tare weight of the bowl was set on the balance and the mixing procedure repeated as for the first half of the mixture. After the mixing was completed, the second portion of the mixture was placed into the flat pan with the first portion and thoroughly mixed with the spoon.

"10. During the last mixing operation, the compaction mold and the upper piston were removed from the oven and set on the concrete floor. A four-inch diameter piece of brown wrapping paper was placed in the bottom of the mold in order to prevent the specimen from sticking to the lower piston.

"11. The mold was filled in four equal layers. Each layer was rodded 25 times with a 3/4-inch round steel bar that weighed 4.6 pounds. After the rodding of the last layer, another paper disk was placed in the mold and the upper piston inserted."

12. The compaction mold with the rodded material was placed in the Riehle compaction machine and was centered under the loading head. In this position both the upper and lower pistons could move inside the mold, thereby allowing compaction of the material from both ends. The

pin holding the lower piston in place was removed. A variable speed selector was used to decrease the speed of the down moving compaction head from 0.1 inch to 0.05 inches per minute until the desired degree of compaction was achieved. During the compaction procedure the mold was vibrated by pounding with a rubber-faced wooden mallet in order to facilitate orientation of the aggregate particles and reduce the amount of crushing. The desired degree of compaction was the density calculated at the design asphalt content. This was achieved by compacting a pre-determined weight of the bituminous-aggregate mixture to a specific height of 10 inches. An Ames dial was used to measure the specific height of 10 inches. Figure 9 shows the compaction of the bituminous-aggregate mixtures with the Ames dial set-up and the mold in the Riehle compaction machine. When the Ames dial gave a reading of 10 inches, the downward movement of the compaction head was stopped by disengaging the gears of the Riehle compaction machine. The compaction load was maintained constantly for two minutes and released by throwing the gears into the reverse direction allowing the compaction head to move upwards.

13. The mold, containing the compacted specimen, then was placed in a circulating cold-water bath and allowed to cool from 8 to 12 minutes. After cooling, the mold was replaced in the Riehle compaction machine, a slight load was applied to the upper piston, and the specimen was forced to move a short distance inside the mold in order to break the adhesion between the specimen and the sides of the mold.

14. The mold was then taken from the compaction device and the bolts removed from each flange. The final loosening of the specimen from the sides of the mold was obtained by gently rocking the mold back and forth. Once loose the mold was removed, and the newly formed specimen

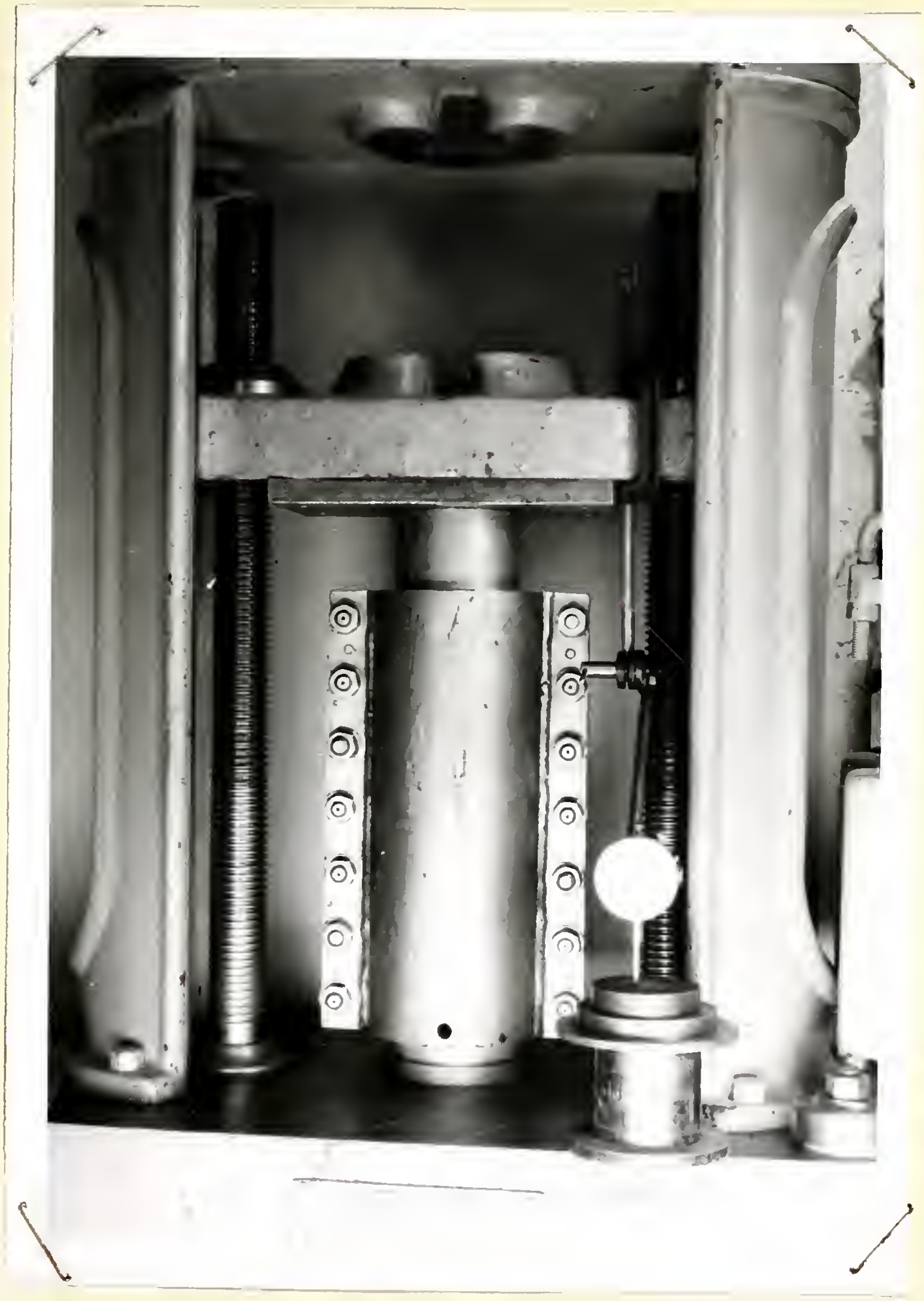
was removed to a convenient storage area. A typical specimen is shown in Plate VII.

15. Before testing, each specimen was weighed on the beam balance, that was accurate to 1.0 gram. Using the same beam balance the specimens were then weighed in water. A third weighing consisted of measuring their saturated surface-dry wights. These values were used in computing the desity of the specimen, and generally as a check on the density at design asphalt content in the case of triaxial and Modified ASTM test specimens. All specimens were then stored at room temperature until needed to be "cured" for testing.

Certain changes were necessitated in this procedure when forming the ASTM and Modified ASTM test specimens.

In the case of the Modified ASTM test specimens, the bituminous-aggregate mixture was compacted to the density required as outlined previously. The resulting specimen of ten inches in height was sawed into two 4-inch high specimens. This was achieved by cutting a two-inch section from the center of each ten-inch specimen. A "Clipper" masonry saw equipped with a diamond blade was used for this purpose. The resulting specimens were measured anf found to be within 4 ± 1/8 inches in height.

The other phase of this study, which consisted of forming ASTM test specimens, involved several important changes which are noted here. The amount of bituminous-aggregate mixture was slected by a trial-and-error procedure so that the resulting height of the test specimen would be 4 ± 1/8 inches. The required amount of bituminous-aggregate mixture was placed in the mold and compacted under a constant load of 3000 psi in the Riehle testing machine for two minutes. This differs from the usual procedure used for triaxial and Modified ASTM test speciems where

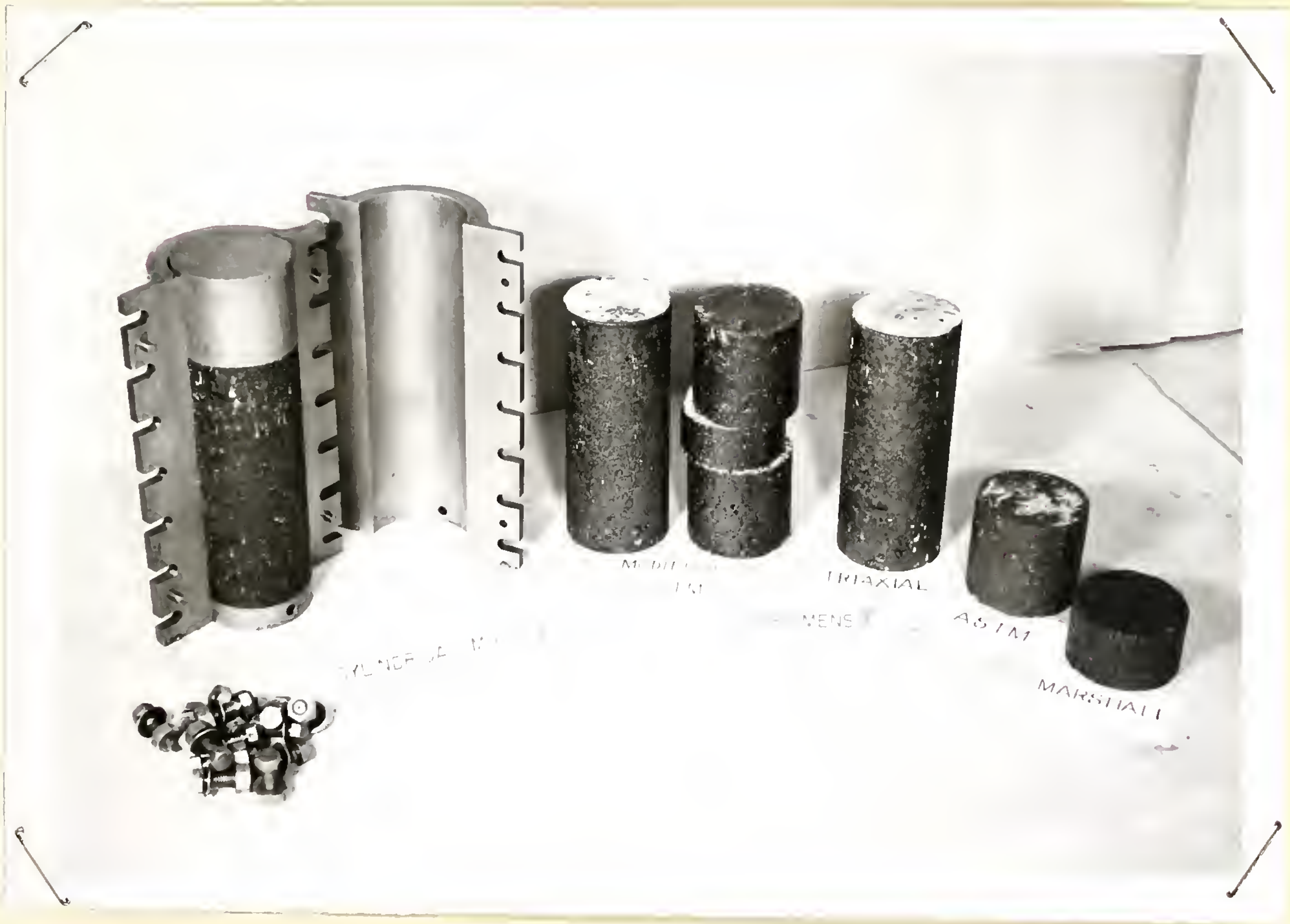


DOUBLE PLUNGER COMPACTION METHOD

For

BITUMINOUS-AGGREGATE MIXTURES

Plate VI



TYPICAL TEST SPECIMENS and UNASSEMBLED MOLD
(Triaxial, Modified ASTM, ASTM and Marshall)

Plate VII

different compactive efforts were applied to obtain a desired predetermined density. A detailed description of the preparation of ASTM test specimens can be found in Reference 2.

Plate VII shows typical ASTM and Modified ASTM test specimens.

Testing the Specimens

Since the testing of each type of specimen follows specific procedures, the following discussion is divided into sub-sections entitled; Triaxial Compression Test, and ASTM and Modified ASTM Compression Test.

Triaxial Compression Test

The apparatus used in the triaxial compression test is as follows: Riehle compression machine with variable speed drive, triaxial cell, rubber membrane, air compressor, and a DeVilbiss air pressure regulator.

A schematic diagram of the triaxial cell is shown in Figure 4 and a general view of the cell and testing apparatus are pictured in Plates VIII and IX. The triaxial cell was designed by the writer and was built by the Central Machine Shop at Purdue University. It will accomodate 4-inch diameter specimens, eight to eleven inches in height. The compressive load, measured by a proving ring, was applied to the specimen through a loading head by a variable speed drive located alongside of the gear box on the Riehle compression testing machine. The loading piston of the triaxial cell moved in a ball bushing provided with a grease seal. The friction was low enough that the piston would move downwards under its own weight. The proving ring was located outside the pressure cell. The pressure cell was made of lucite. Main-line air pressure of approximately 35 psi. was provided by a Hobart air compressor and was regulated

by a DeVilbiss air pressure regulator.

Immediately prior to testing in the triaxial cell, the test specimens were maintained at the testing temperature of 80± 5° F. for at least four hours. It was found that the specimen temperature after testing did not differ more than ± 1° F. from the temperature before testing.

After the specimens were cured and the correct temperature in the testing room obtained, the testing was accomplished according to the following detailed procedure:

1. A rubber membrane (4-inch diameter, 12-inch length, and 0.015-inch thick) obtained from Soiltest, Inc. (Chicago) was rolled up and fitted over the lower testing head. The specimen was placed on the lower testing head and the rubber membrane rolled up over the specimen.

2. A light coat of rubber cement was placed on the upper and lower testing heads to provide an air tight seal between the rubber membrane and the testing heads. After the membrane had been cemented to the heads, additional security was obtained by binding the membrane to the heads with several rubber bands.

3. The specimen was centered on the lower testing head, the upper testing head was centered on the specimen, and the lucite cylinder was lowered over the specimen into position. The loading piston, inserted through the bushing in the cover plate, was then centered in the depression on the upper testing head by adjusting the position of the cover plate. The three connecting bolts were then placed in position and the apparatus tightened together.

4. The main-line air pressure valve was opened. The valve in the lower drainage line was shut and air under a pressure of approximately

DETAILS OF TRIAXIAL CELL

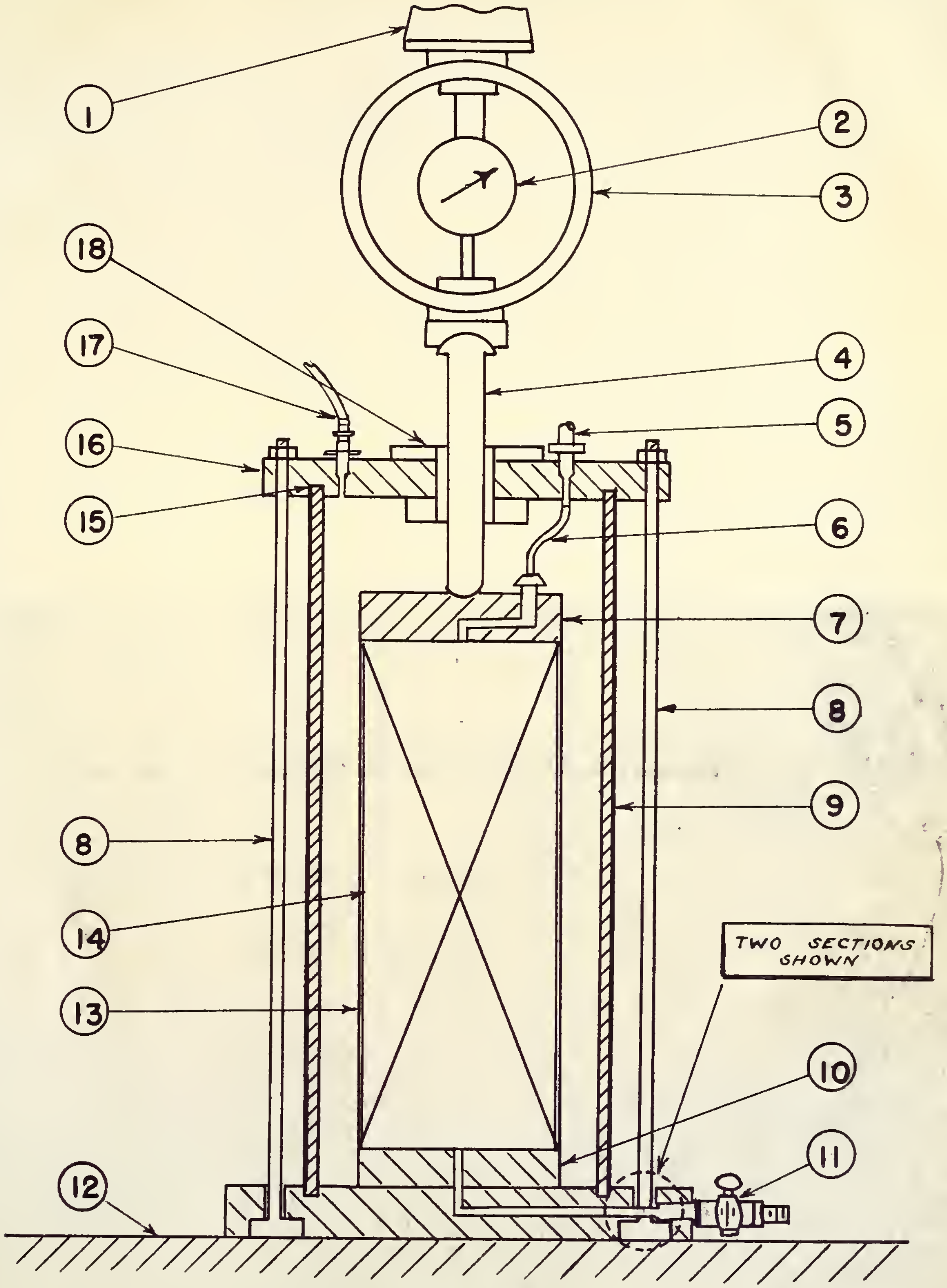


FIGURE 4

Details of Triaxial Cell

1. Loading head
2. Proving ring deflection dial
3. Proving ring
4. Loading piston
5. Upper drainage valve
6. Upper drainage line
7. Upper testing head
8. Connecting bolts.
9. Cylindrical wall of triaxial pressure cell
10. Lower testing head
11. Lower drainage line and drainage control valve
12. Table of testing machine
13. Rubber membrane
14. Test specimen
15. Recess for cylinder
16. Cover plate
17. Compressed air inlet line
18. Ball bushing with low-friction grease seal

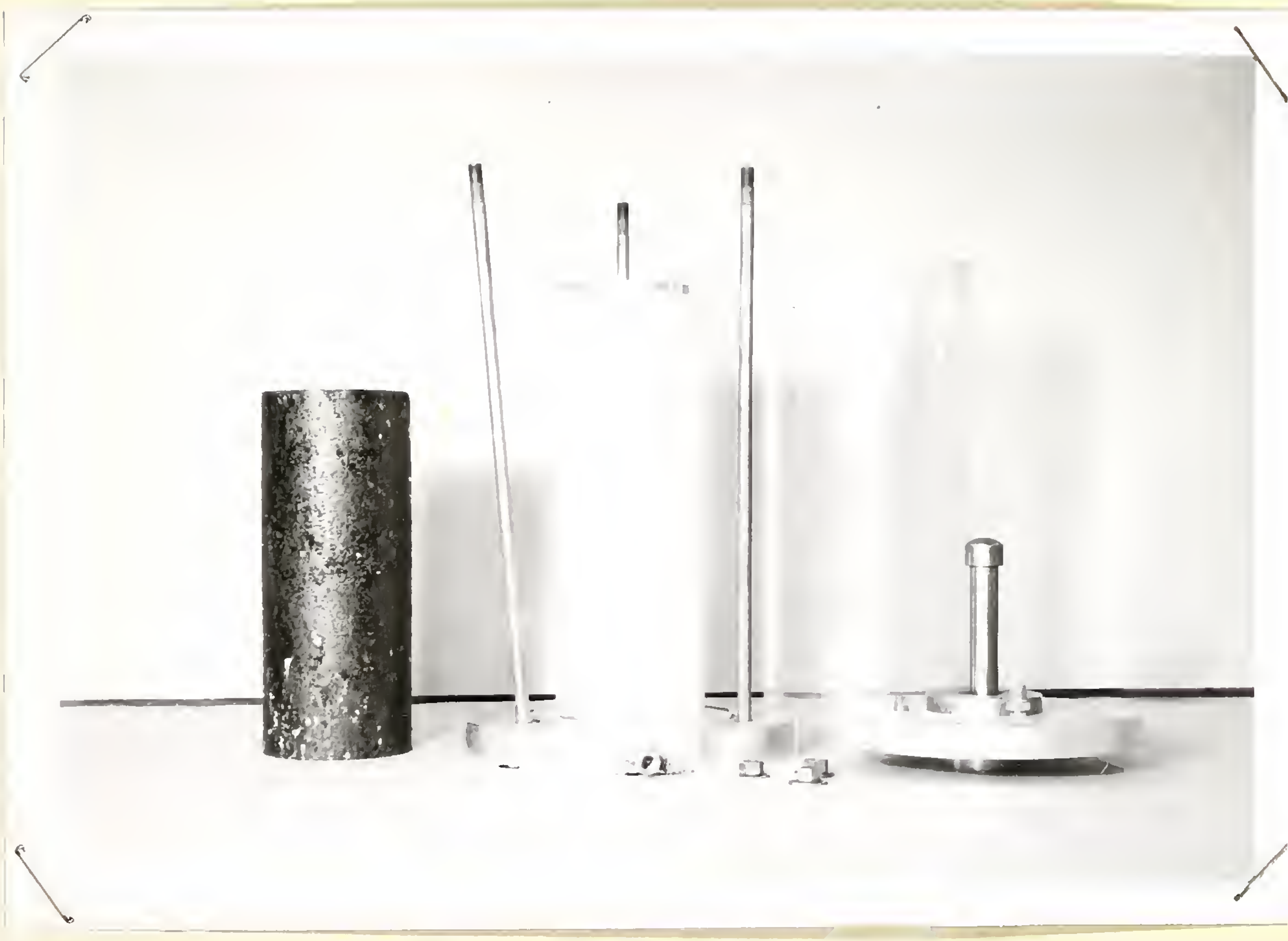
30 psi. was allowed to enter the chamber. After three minutes the lower drainage valve was opened in such a manner that escaping air would cause a squeal. However, if there was no air loss detected by this method, the membrane was assumed to be air tight. If a leak occured, usually the rubber bands were removed from the testing heads and additional rubber cement was used to obtain a new seal. This new seal was then tested as before. If this was not sufficient, the leak was in the rubber membrane itself, and this situation could be remedied by either patching or replacing with a new membrane.

5. After the entire apparatus was placed and centered under the proving ring, the motor of the Riehle compression machine was put into gear and the loading head with the proving ring moved downward until a small seating load of one division on the load dial (about 10 pounds) was applied.

6. The air line was attached to the triaxial cell from the air regulator end. Confining air pressure inside the pressure chamber of the triaxial cell was regulated to 15 or 30 psi. by means of the DeVilbiss air regulator. The apparatus at this stage of the operation is pictured in Plate IX.

7. The variable speed motor was set to give a rate of strain of 0.05 inch per minute and the loading started. As the specimen was loaded, constant attention was given to the possible development of air leaks. Loading was continued until the maximum compressive load was obtained.

8. At the end of the test the drive motor was stopped, the air was released from the pressure cell, and the load was removed by reversing the direction of the movement of the loading head. The appara-



UNASSEMBLED TRIAXIAL APPARATUS

with

SPECIMEN

Plate VIII

tus was then disassembled and the specimen removed.

ASTM and Modified ASTM Compression Test

Testing of ASTM and Modified ASTM specimens does not differ in any respect from the standard ASTM procedure as outlined in the "ASTM Compressive Strength Test for Bituminous Mixtures (ASTM Designation: D1074-52T)," Reference (2). The following is a brief discussion of the compression test method:

1. The test specimens were prepared for test after they had been cured for at least 24 hours in an oven at a temperature of 140° ± 5° F. After removal from the oven the test specimens were placed in an air bath for not less than 4 hours at 77± 1° F.

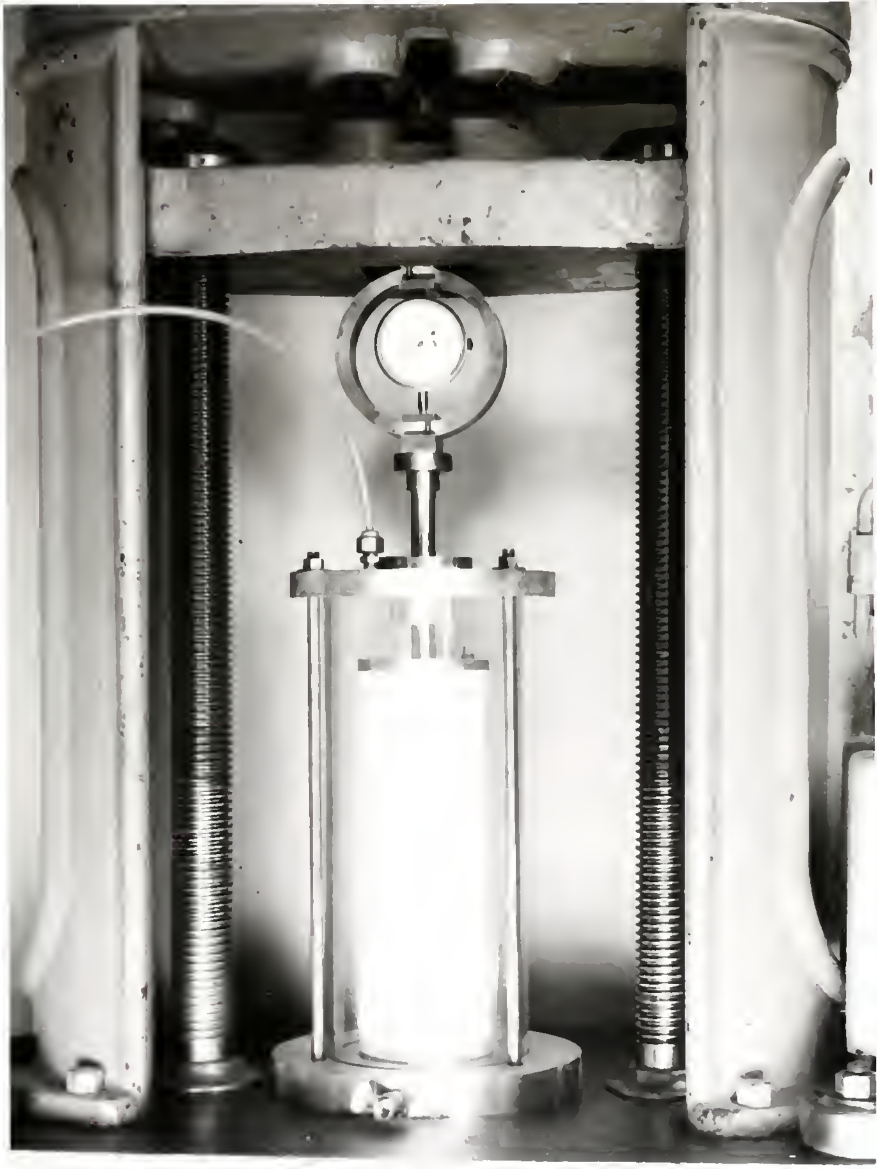
2. After removal from the air bath the specimen to be tested was centered on a spherically-seated base, and a loading head was centered over the specimen.

3. The entire assembly was then centered under the proving ring attached to the loading head of the Riehle compression machine.

4. The variable speed motor was started and the proving ring and loading head were lowered until the load dial registered one division (a small seating load of 10 pounds). The motor was stopped and the load dial was reset to zero.

5. After re-starting the variable speed motor and adjusting to a speed of 0.2 inch per minute, loading was started and continued until the maximum compressive load was reached.

6. The load was removed by reversing the movement of the loading head at the end of the test. The apparatus was then disassembled and



GENERAL VIEW OF TRIAXIAL APPARATUS READY FOR TEST
(Air Pressure Gauge and Regulator Not Shown)

Plate IX

and the specimen removed.

7. The maximum compressive load, in pounds, was recorded.

Plate X shows the ASTM compression test in progress.

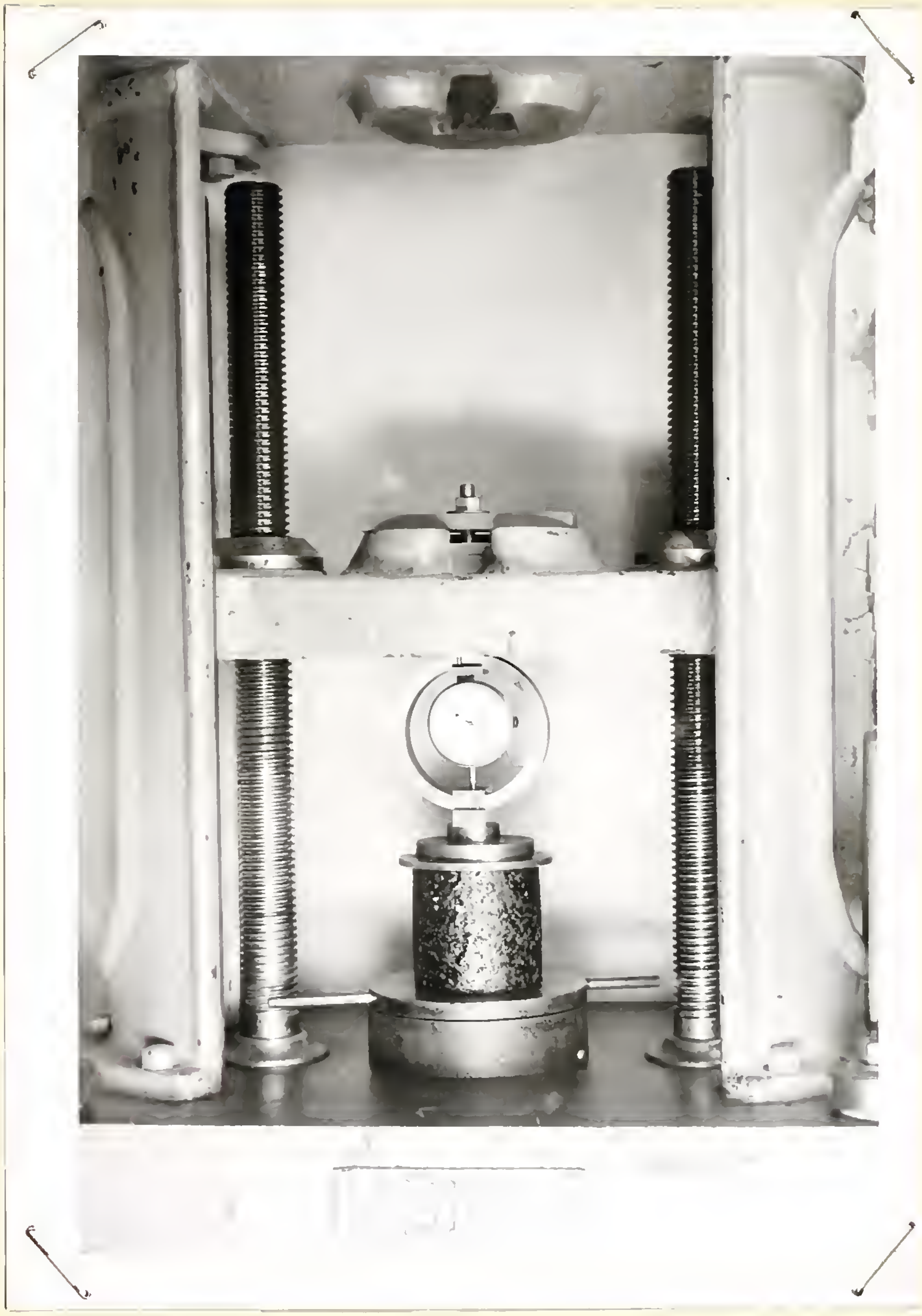
Extraction Tests for Determining Asphalt Distribution

Since it was desired that analyses be made of the controlled dese-graded bitimunious-concrete mixtures (Corps of Engineers' Minimum Gradation) in order to explain a possible relationship between the distribution of asphalt within these mixtures and the properties of cohesion and internal friction as compared with those in sand-asphalt mixture, asphalt extraction tests were run on these mixtures.

The primary purpose of the test in this investigation was to determine the percentage of asphalt contained in both the fine-aggregate and coarse-aggregate portions of the bituminous-concrete mixtures. These test values were then used to determine a change in the distribution of asphalt between fine and coarse aggregate as the percentage of crushed-gravel fine aggregate, or crusher dust, changed in the fine aggregate fraction of the bituminous-aggregate mixture.

The asphalt extraction procedure followed closely to the standard Centrifugal Method suggested by the American Association of State Highway Officials (AASHO Designation: T58-57). This method is outlined in Reference (1).

The apparatus used in this test procedure was: A "Dulin Rotarex" centrifugal extractor, "Peerless" gas oven, U.S. Standard No. 4 sieve, flat pan, enamel-ware pans, a torsion balance, solvent, a recepticle flask, and filter paper.



ASTM COMPRESSION TEST IN PROGRESS
(ASTM and Modified ASTM Test Specimens)

Plate X

A discussion of the test procedure follows:

1. The samples that were tested consisted of a group of the dense-graded bituminous-concrete triaxial specimens. Each sample, approximately 5000 grams, was prepared for analysis by heating it in a flat pan in the gas oven to approximately 270° F. At this temperature the sample was easily broken up and the fluidity of the asphalt caused the bituminous-aggregate mixture to become "workable".

2. A heated No. 4 sieve was taken out of the top shelf of the oven and placed over a flat, tared pan on the second shelf of the oven. The regulator on the oven was turned to 450° F. in order to compensate for the loss of heat to the outside air during sieving of the bituminous-aggregate mixture. It furnished a temperature inside the oven of approximately 275° F.

3. The disintegrated sample was separated into several sections in the pan. Each section was removed with a warm spoon and the material placed on top of the No. 4 sieve. A flat-end spatula was then used to work the material over the sieve. The coated fine aggregate material passing through the sieve fell in the tared pan underneath.

4. When no more of the material passed through the sieve, the bituminous-aggregate material remaining on the sieve was transferred to a second tared pan.

5. This procedure continued until the entire sample was separated.

6. The pan containing the coated fine aggregate material passing the No. 4 sieve was weighed and placed aside. The pan containing the coated aggregate material retained on the No. 4 sieve was weighed and 100 ml. of benzene added to the material in the pan.

7. After working the benzene into the bituminous-aggregate mixture,

the pan and mixture were placed alongside the centrifugal extractor.

8. Aproximately 900 g. of the material was removed from the pan and placed in the bowl of the centrifugal extractor.

9. A piece of filter paper was fitted on the top rim of the bowl, after which the cover plate was placed in position and drawn down tightly by means of the milled nut.

10. The bowl was then placed on the motor shaft of the extractor and the slot and pin were carefully locked. An empty flask was placed under the spout and 150 cc. of benzene was poured into the bowl through the top hole.

11. After allowing the material to digest for a few minutes, the motor was started, slowly at first, in order to permit the aggregate to distribute uniformly. The motor speed was then increased sufficiently by means of the regulator to cause the dissolved bitumen to flow from the spout in a thin stream.

12. When the first charge had drained, the motor was stopped and a fresh portion of benzene was added. This operation was repeated from seven to nine times with 150 cc. of benzene.

13. When the last addition of benzene had drained off, the thin stream from the spout being observed to be clear, the bowl was removed and placed with the coverplate uppermost on a sheet of manila paper.

14. The cover plate and filter paper were carefully laid aside on the paper ~~[illegible]~~; when the sample was thoroughly dry, it was brushed into a tared pan.

15. This procedure (8 to 14) was repeated for each portion of the material in the pan. Then the entire dry aggregate sample was weighed.

16. The difference between the weight of the final sample and the original amount taken gave the amount of bitumen extracted, which was subject to correction, dependent on the amount of ash in the filter paper and in the washings.

17. The ash correction was made in the following two manners:

a. The amount of ash in the filter paper was determined by burning the filter paper in the pan containing the dry aggregate after extraction. The filter paper was of such nature that after burning the ash remaining would be only the fine material of the aggregate portion, eg. the filter paper itself burned ash-free.

b. An additional ash correction was determined on an aliquot portion of the bituminous-solvent material in the recepticle flask. The total solution of bitumen, well stirred, was measured and an aliquot portion of 100 cc. was taken and poured into a previously weighed evaporation dish. The solvent was evaporated over a steam bath and the residual asphalt was then ignited over a meeker burner and in a high-temperature "Hoskins" electric furnace. The dish and contents were then cooled in a dessicator and the percentage of ash calculated.

18. The total corrected weight of aggregate was then calculated as a summation of the ash corrections and the dry aggregate removed from the bowl after the extraction test.

19. The asphalt in the coated fine aggregate material passing the No. 4 sieve was extracted by the same procedure previously outlined in paragraphs 6 to 18.

The portion of the aggregate retained on the No. 4 sieve contained a certain percentage of the fine aggregate fraction as well as the entire coarse aggregate fraction. The exact amount of the fine aggregate frac-

tion was determined by sieving the dry "coarse" aggregate portion through the No. 4 sieve. The material passing the No. 4 sieve usually varied from 20 to 60 grams. This was a small percentage of the total fine-aggregate fraction which weighed approximately 2750 grams in each sample. A correction was applied, however, for the fines in the coarse aggregate.

The following page contains sample data from a typical extraction test on a sample. It shows the test procedure for calculating the percentage of asphalt in each aggregate fraction along with the applied corrections.

DATA SHEET

CENTRIFUGAL EXTRACTION TEST - ASPHALT COATING AGGREGATE

Sample NO. 2 , Type Dense-Graded Bituminous Concrete

Percent Crusher Dust in Fine Aggregate 50 %

Total Weight of Specimen 4766 g.

Weight of : Coarse Aggregate 2145 g., Fine Aggregate 2621 g.

Percent of Asphalt (% by aggregate wt.) 4.9 %, Amt. 235 g.

Weight of Pan 502 g.

Aggregate Retained on No. 4 Sieve

Pan + Wt. of Asphalt & Aggregate Retained on No. 4 Sieve 2760 g.
Wt. of Asphalt & Aggregate Retained on No. 4 Sieve 2760-502 = 2258 g.
Extraction Test:
Wt. of Pan & Aggregate Retained on No. 4 Sieve * 2700 g.
Ash Correction:
For 100 cc. Aliquot Portion, 0.07 g.
For 1232 , cc., 12.32 x 0.07 = 0.86 g. , or 1 g.
Total Wt. of Aggregate Retained on No. 4 Sieve (2700+1)-502 = 2199 g.
Wt. of Asphalt in Aggregate Retained on No. 4 Sieve 2258-2199 = 59 g.
Amt. of Fine Aggregate in Aggregate Ret. on No. 4 Sieve ** 41+1 = 42 g.
(Theo. Wt. 2188-2145 = 43 g)

Aggregate Passing No. 4 Sieve

Pan + Wt. of Asphalt & Aggregate Passing No. 4 Sieve 3872 g.
Wt. of Asphalt & Aggregate Passing No. 4 Sieve 3872-502 = 3370 g.
Extraction Test:
Wt. of Pan & Aggregate Passing No. 4 Sieve* 3693 g.
Ash Correction:
For 100 cc. Aliquot Portion, 0.19 g.
For 1512 cc., 15.12 x 0.19 = 2.88 g. , or 3 g.
Total Wt. of Aggregate Passing No. 4 Sieve (3693+3)-502 = 3194 g.
Wt. of Asphalt in Aggregate Passing No. 4 Sieve 3370-3194 = 176 g.
Percent Asphalt in Aggregate Passing No. 4 Sieve 176/3194 x 100 = 55 %
Asphalt Correction for Fine Aggregate in Aggregate Retained on No. 4 Sieve:

0.055 x 42 g. = 2.3 g. , or 2 g.

Total Weight of Asphalt in Fine Aggregate 176+2 = 178 g.

Total Weight of Asphalt in Coarse Aggregate 59-2 = 57 g.

Percent Asphalt in Mix Coating Fine Aggregate 178/235 x 100 = 76 %

Percent Asphalt in Mix Coating Coarse Aggregate 57/235 x 100 = 24 %

Percent Asphalt Coating Fine Aggregate (%Wt. of fine agg.) 178/2621 x 100 = 6.8 %

Percent Asphalt Coating Coarse Aggregate (% Wt. of coarse agg.) 57/2145 x 100 = 2.7 %

---

* Filter paper burned in pan with extracted dry aggregate.
** After re-sieving on No. 4 sieve.

RESULTS

Strength or stability test data were collected in this investigation on bituminous-concrete and sand-asphalt surface mixtures prepared with variable percentages of crushed-gravel fine aggregate. In addition, data were obtained on the distribution of asphalt between coarse and fine aggregate in the controlled dense-graded bituminous-concrete mixtures.

Strength or stability data from laboratory tests were obtained on sand-asphalt mixtures and two groups of bituminous-concrete mixtures that differed in gradation. The sand-asphalt mixtures and one of the groups of bituminous-concrete mixtures adhered to specific dense-gradation as the percent of crushed aggregate was varied. They were made with a laboratory-controlled crusher dust-natural aggregate gradation adhering to the Corps of Engineers' minimum specifications. The other group of bituminous - concrete mixtures contained crusher dust-natural aggregate gradations within ASTM specifications for these types of mixtures. In these latter mixtures two plant-run sands, crusher dust and Indiana No. 17 sand, were blended as received with the gravel coarse aggregate.

Graphical representations of the test results are given in this section in Figures 5 to 12. The tabulated data are represented in Tables 6 to 13 in Appendix B.

Compressive strength or stability values versus percent crusher dust in the fine aggregate are plotted in Figures 6, 7, and 8. ASTM, Modified ASTM, and triaxial compressive strength values at 15 and 30 psi. lateral pressures are presented in pounds of maximum comprssive load rather than in pounds per square inch maximum compressive strength in order to present a comparison with the Marshall stability values at design

asphalt content.

In this presentation the results are given under five general headings: (a) Mixture Density and Design Data, (b) Strength Test Results of Controlled Dense-Graded Bituminous-Concrete Mixtures, (c) Strength Test Results of Controlled Dense-Graded Sand-Asphalt Mixtures, (d) Strength Test Results of Bituminous-Concrete Mixtures within ASTM Specifications, and (e) Comparison of Bituminous-Concrete and Sand-Asphalt Triaxial Strength Characteristics.

Mixture Density and Design Data

Tables 6 and 7 in Appendix B are given the design asphalt contents determined by the Corps of Engineers' design procedure for the mixtures studied in this investigation. Marshall Stability anf Flow, percent voids, percent voids filled with asphalt, and density values at design asphalt contents also are given in Tables 6 and 7 of Appendix B.

The Corps of Engineers' design procedure utilizing the Marshall Test gave the design asphalt contents for each bituminous-aggregate mixture containg the various percentages of crusher dust and natural sand.

TABLE 5

Design Asphalt Contents of Bituminous-Aggregate Mixtures

Mixture Type	Crusher Dust Percent by Weight of Fine Aggregate	Asphalt Content Percent by Weight of Aggregate
Bituminous-Concrete (C.E. Min. Gradation	0	4.6
	25	4.8
	50	4.9
	75	5.1
	100	5.5
Sand-Asphalt (C.E. Min. Gradation)	0	6.3
	25	6.6
	50	6.9
	75	7.1
	100	7.2
Bituminous-Concrete Crusher dust-Natural aggregate blends (ASTM Gradations)	0	-
	25	5.4
	50	5.5
	75	5.5
	100	5.6

The data in Tables 5, 6 and 7 show increased values of the design asphalt content for all the mixtures as the percentage of crusher dust in the fine aggregate was increased. The sand-asphalt mixtures had the highest design asphalt contents. For the bituminous-concrete mixtures within ASTM specifications, the design asphalt content values did not vary greatly as the amount of crushed dust was increased and were near the upper values for the design asphalt contents determined for the controlled dense-graded bituminous-concrete mixtures. In the controlled dense-graded bituminous-concrete mixtures, the design asphalt contents varied over a greater range of values than those in the bituminous-concrete mixtures within ASTM specifications.

Marshall Flow values, given in Tables 6 and 7, generally show a

trend of decreasing or constent values in both the controlled dense-graded and ASTM specification-type bituminous-concrete mixtures as amounts of crusher dust increases, while in the controlled dense-graded sand-asphalt mixtures the Flow values increased as the percentage of crusher dust in the fine aggregate was increased.

Tables 6 and 7 list the unit weights of the bituminous-concrete and sand-asphalt mixtures at their design asphalt content. Unit-weight values at design asphalt content were the highest in the controlled dense-graded bituminous-concrete mixtures (150.9 to 151.3 lb./cu.ft.). In the controlled dense-graded sand-asphalt mixtures the unit-weight values are lower(144.3 to 146.5 lb./cu.ft.) at the design asphalt content than in the controlled dense-graded bituminous-concrete mixtures (150.9 to 151.3 lb./cu.ft.). The bituminous-concrete mixtures that consisted of aggregate gradations within ASTM specifications (Table 7) had unit-weight values generally between the unit-weight range of the controlled dense-graded sand-asphalt and bituminous-concrete mixtures (144.1 to 149.3 lb./cu.ft.).and with a greater range of values.

Figure 5 shows plots of test-specimen density versus percent crusher dust in the fine aggregate for all mixtures. Unit-weight data for specimens computed by ASTM procedure are found in Tables 10, 11 and 12. There was a change in density depending upon the compaction method and the gradation of the aggregate used in the mixture.

The variation in density that resulted from the compaction method is illustrated by the plots of the density values resulting from the ASTM method of compaction and the density values resulting from the Corps of Engineers' compaction method. These density values are shown in Figure 5 and identified by ASTM notation on the one hand and Marshall,

triaxial, and Modified ASTM notation on the other. The greatest range in density of the test specimens that resulted from varying percentages of crusher dust in the fine aggregate occurred with the ASTM compaction procedure.

The type of mixture influenced density when the compaction procedure for the test specimens remained the same. The greatest density values were those that resulted from the compaction of the controlled dense-graded bituminous-concrete mixtures and the bituminous-concrete mixtures within ASTM specifications. The test specimens that consisted of bituminous-concrete mixtures within ASTM specifications had the greatest change in density when the percentage of crusher dust increased in the fine aggregate.

Table 10 and Figure 5 show that density produced by ASTM compaction was less than density produced by Modified ASTM compaction for any given percentage of crusher dust in the fine aggregate fraction of the controlled dense-graded bituminous-concrete mixtures. For the controlled dense-graded sand-asphalt mixtures, the density values of the ASTM specimens (Table 11) are less than the density values of the Modified ASTM test specimens up to 50 percent crusher dust in the mixture, and thereafter as the percentage of crusher dust increased from 50 to 100 percent, the density values of the ASTM test specimens were greater. For the bituminous-concrete mixtures within ASTM specifications, Table 12 and Figure 5 show the density values of the ASTM compacted test specimens to be greater than the density values of the Modified ASTM test specimens when more than 50 percent of crusher dust was used in the fine aggregate.

COMPARATIVE DENSITIES OF TEST SPECIMENS VS. PERCENT CRUSHER DUST

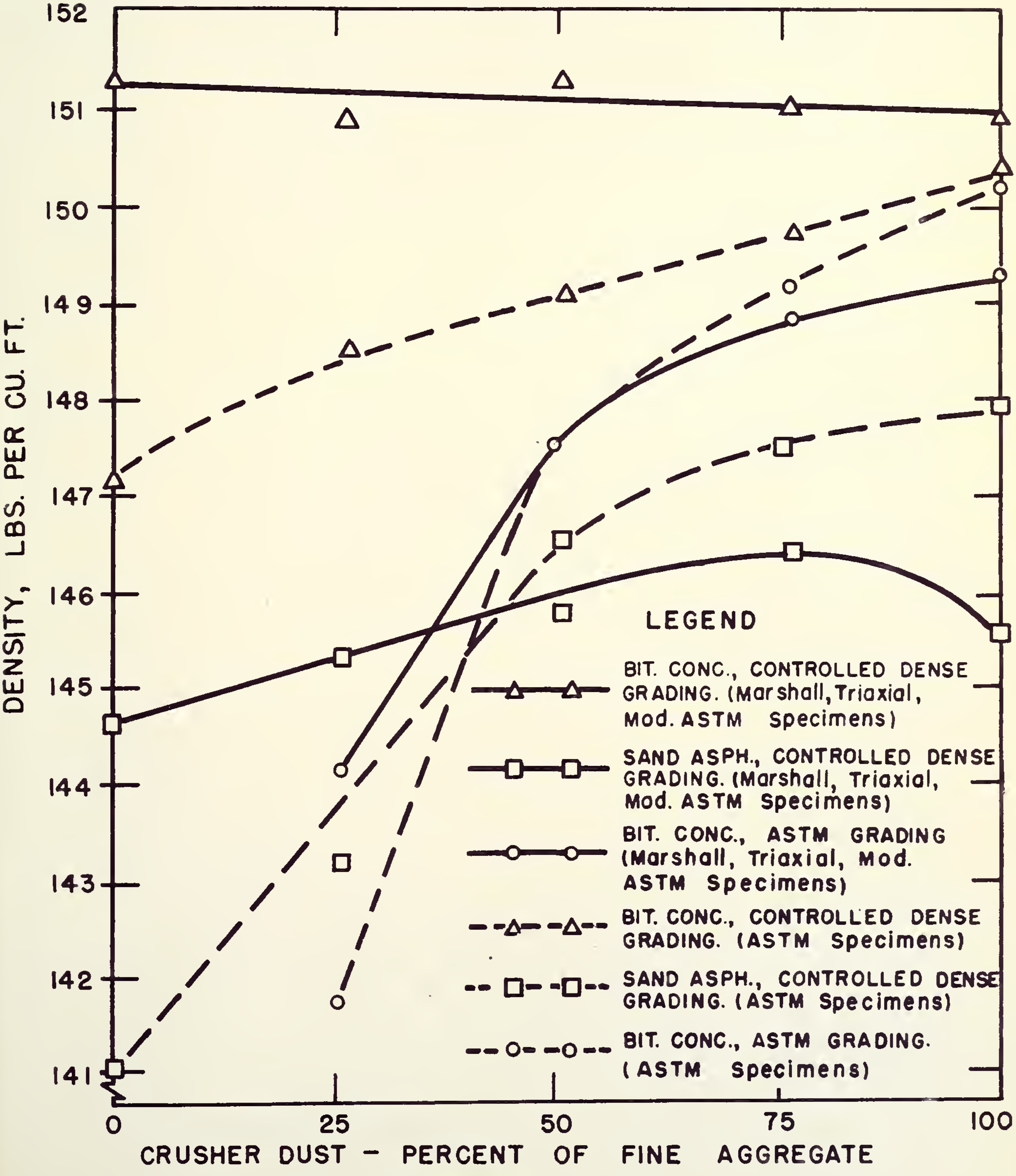


FIGURE 5

Strength Test Results of Controlled Dense-Graded Bituminous-Concrete Mixtures

Compressive strength or stability values versus percent crusher dust in the fine aggregate are shown graphically in Figure 6 for the bituminous-concrete mixtures with controlled (Corps of Engineers') dense grading. These data are also presented in Tables 6, 8 and 10 in Appendix B.

In general, the results of the strength tests used in this investigation show increased compressive strength or stability values for these mixtures when the percent of crusher dust in the fine aggregate was increased.

Triaxial strength data are shown graphically in Figure 6 and presented in Table 8. With a given percentage of crusher dust, the compressive strength values at lateral pressures of 30 psi. were greater than those at lateral pressures of 15 psi. The compressive strength curves representing each lateral pressure had approximately the same shape. The compressive strength values at each lateral pressure increased with an increased percentage of crusher dust in the fine aggregate.

Figure 6 and Table 6 show that Marshall Stability values at design asphalt content increased to a maximum load value when the percentage of crusher dust in the fine aggregate increased to 50 percent, and at percentages of crusher dust in the fine aggregate greater than 50 percent, the Marshall Stability values remained approximately the same. The Marshall Stability values were lower than the compressive strength values obtained from other tests used in this investigation for any given percentage of crusher dust in the fine aggregate.

ASTM and Modified ASTM compressive strength data are presented in

COMPRESSIVE STRENGTH OR STABILITY
VS.
PERCENT CRUSHER DUST

BITUMINOUS-CONCRETE MIXTURES

(Controlled Dense — Graded)

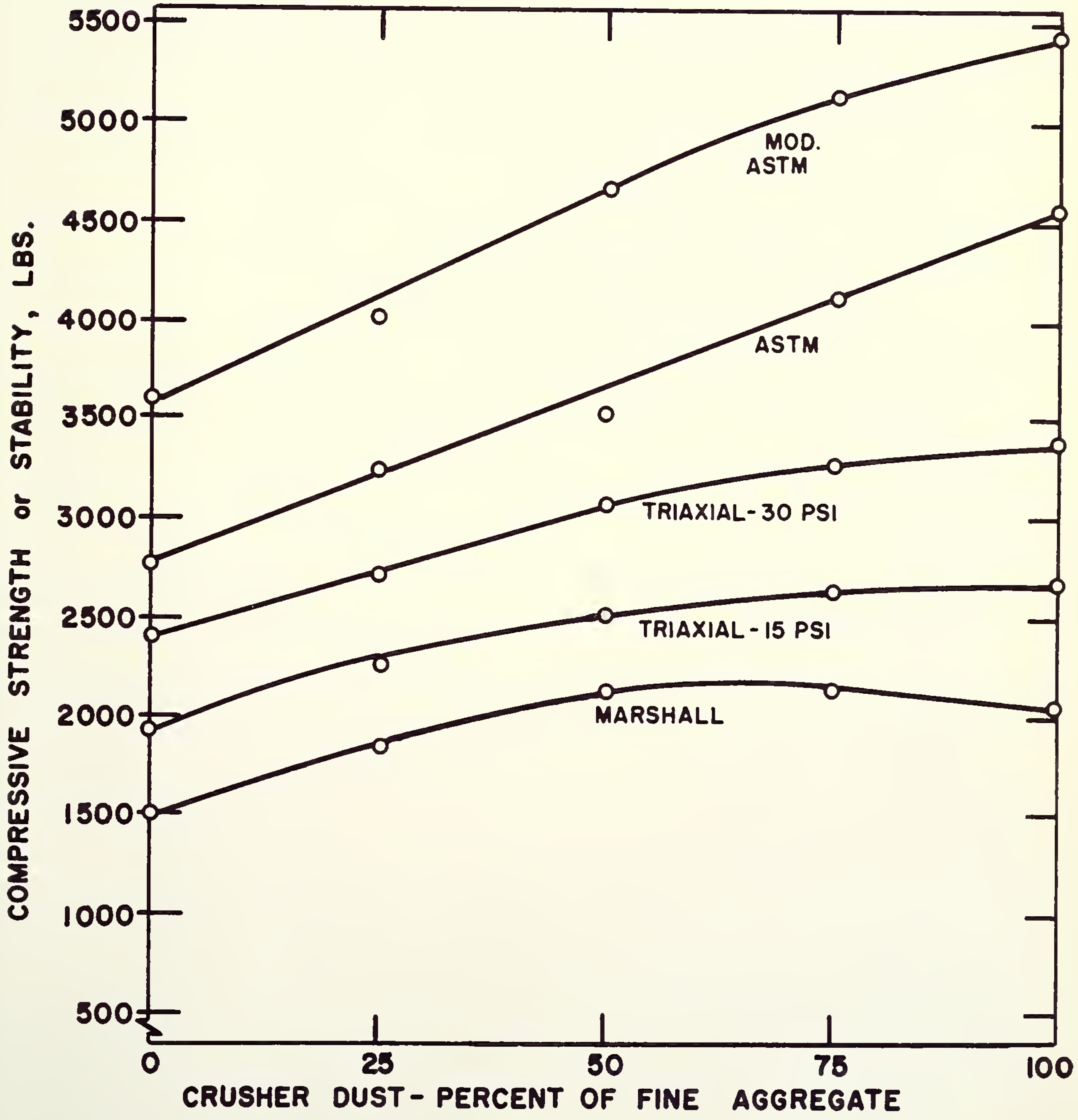


FIGURE 6

Table 10 and shown graphically in Figure 6. Figure 6 shows increased compressive strength values from ASTM tests for the Modified ASTM and the ASTM test specimens when the percentage of crusher dust increased in the fine aggregate. The compressive strength values for Modified ASTM specimens were greater than values for ASTM specimens for any given percentage of crusher dust in the fine aggregate fraction. The compressive strength values for Modified ASTM and ASTM specimens were the highest strength values obtained when compared with the triaxial test and Marshall Stability values at any given percentage of crusher dust in the fine aggregate.

Strength Test Results of Controlled Dense-Graded Sand-Asphalt Mixtures

Compressive strength or stability values versus percent crusher dust for the controlled (Corps Engineers') dense-graded sand-asphalt mixtures are shown graphically in Figure 7. These data are also presented in Tables 6, 8 and 11 in Appendix B.

The results of all the tests used in this investigation on these mixtures showed increased compressive strength or stability values when the percentage of crusher dust was increased. With a given percentage of crusher dust, the compressive strength values at lateral pressures of 30 psi. were greater than those at lateral pressures of 15 psi.. The compressive strength curves representing each lateral pressure had approximately the same shape. The compressive strength values at each lateral pressure increased with an increased percentage of crusher dust.

Figure 7 and Table 6 show that Marshall Stability values at design

COMPRESSIVE STRENGTH OR STABILITY
VS.
PERCENT CRUSHER DUST

SAND-ASPHALT MIXTURES

(Controlled Dense — Graded)

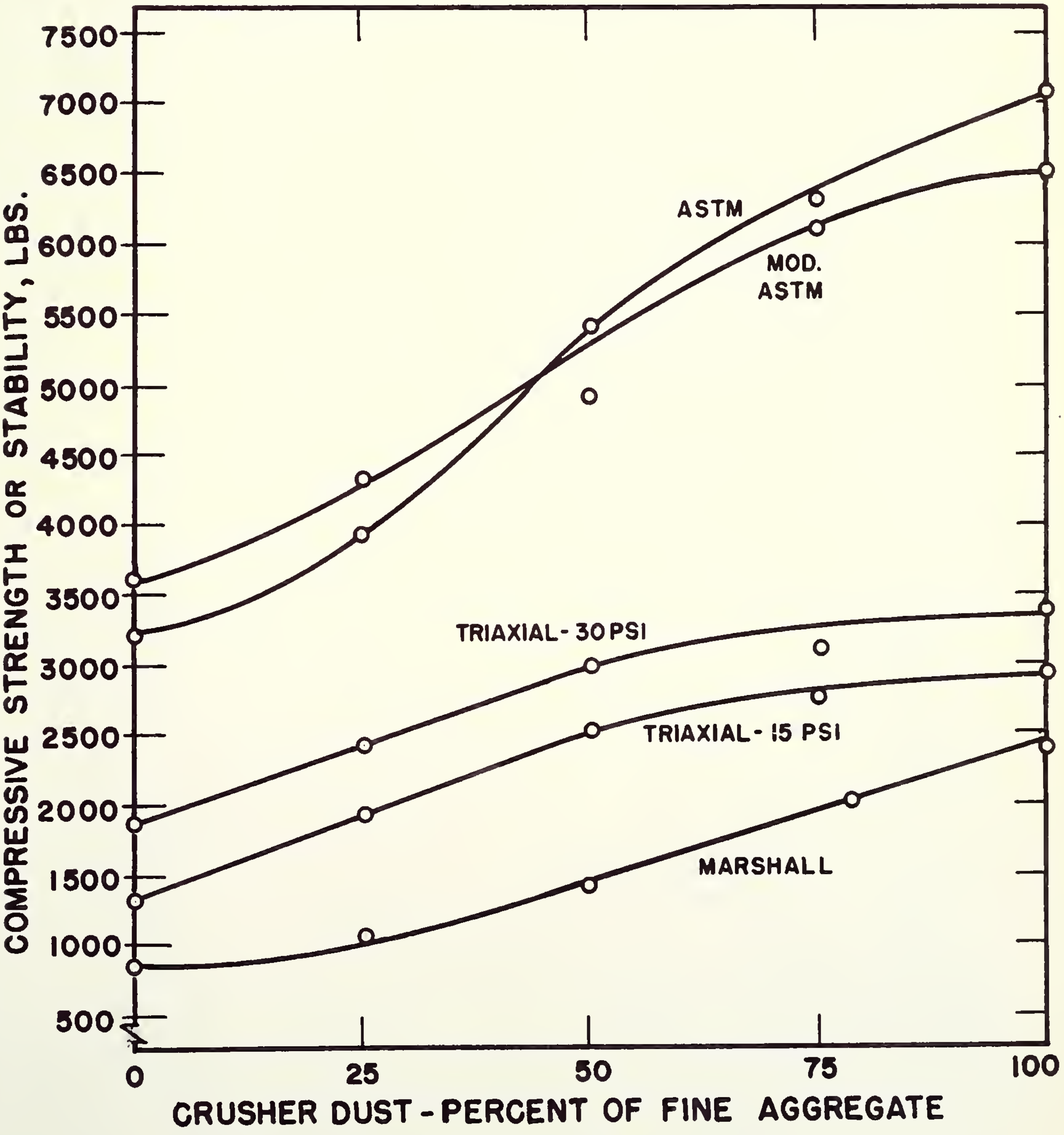


FIGURE 7

asphalt content increased with an increased percentage of crusher dust. The Marshall Stability values were lower than the compressive strength values obtained from other tests used in this investigation for any given percentage of crusher dust.

Compressive strength data for ASTM and Modified ASTM test specimens are presented in Table 11 and shown graphically in Figure 7. Figure 7 shows increased compressive strength values from ASTM tests for the Modified ASTM and ASTM test specimens when the percentage of crusher dust was increased. The compressive strength values for ASTM specimens were greater than for Modified ASTM specimens for given percentages of crusher dust greater than 50 percent. The ASTM compressive strength values for ASTM and Modified ASTM specimens were the highest strength values obtained when compared with the triaxial test values and Marshall Stability values for any given percentage of crusher dust.

Strength Test Results of Bituminous-Concrete Mixtures within ASTM Specifications

Compressive strength or stability values versus percent crusher dust in the fine aggregate are shown graphically in Figure 8 for bituminous-concrete mixtures within ASTM specifications. These data are also presented in Tables 7, 9 and 12 in Appendix B.

The results of all the tests used in this investigation on these mixtures show increased compressive strength or stability values when the percentage of crusher dust in the fine aggregate was increased.

With a given percentage of crusher dust, the compressive strength values at lateral pressures of 30 psi. were greater than those at lateral pressures of 15 psi. The compressive strength curves representing

COMPRESSIVE STRENGTH OR STABILITY VS. PERCENT CRUSHER DUST

CRUSHER DUST–NATURAL AGGREGATE BLENDS WITHIN ASTM SPECIFICATIONS

BITUMINOUS–CONCRETE MIXTURES

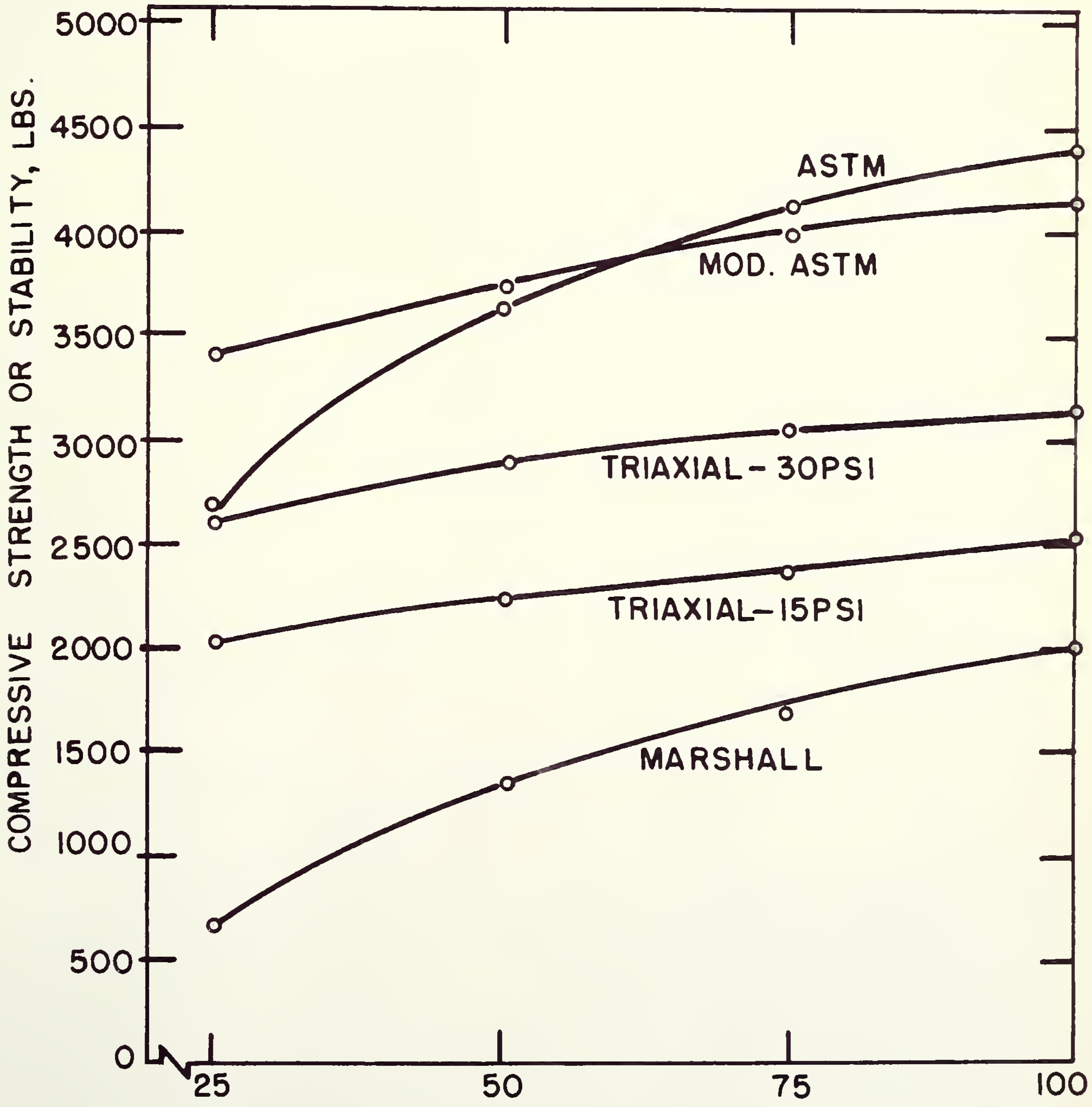


FIGURE 8

each lateral pressure had approximately the same shape. The compressive strength values at each lateral pressure increased with an increased percentage of crusher dust in the fine aggregate.

Figure 8 and Table 7 show that Marshall Stability values at design asphalt content increased when the percentage of crusher dust in the aggregate increased. The Marshall Stability values were lower than the compressive strength values obtained from other tests used in this investigation for any given percentage of crusher dust in the fine aggregate.

Compressive strength data for ASTM and Modified ASTM test specimens are presented in Table 12 and shown graphically in Figure 8. Figure 8 shows increased compressive strength values from ASTM tests for the Modified ASTM and ASTM test specimens when the percentage of crusher dust increased in the fine aggregate. The compressive strength values for ASTM specimens were greater than for Modified ASTM specimens at given percentages of crusher dust in the fine aggregate greater than 75 percent. The compressive strength values for ASTM and Modified ASTM specimens were the highest strength values obtained when compared with the triaxial test and Marshall Stability values for any given percentage of crusher dust in the fine aggregate.

Comparison of Bituminous-Concrete and Sand-Asphalt Triaxial Strength Characteristics

The triaxial strength characteristics of cohesion and angle of internal friction for the bituminous surface mixtures studied in this investigation are presented in Tables 8 and 9 in Appendix B and shown graphically in Figures 9, 10 and 11.

Controlled Dense-Graded Bituminous-Concrete Mixtures

Triaxial test results showing the relationships between cohesion and angle of internal friction and the percent of crusher dust in the fine aggregate for dense-graded bituminous-concrete mixtures are presented in Figure 9. Figure 9 shows increased values of cohesion and angle of internal friction when the percentage of crusher dust in the fine aggregate fraction was increased. Cohesion increased from 39.0 to 47.0 psi. and the angle of internal friction increased from 26.1 to 38.7 degrees when the percentage of crusher dust in the fine aggregate was increased from 0 to 100 percent.

Controlled Dense-Graded Sand-Asphalt Mixtures

Triaxial test results showing the relationship between cohesion and angle of internal friction and percent of crusher dust for dense-graded sand-asphalt mixtures are presented in Figure 10. Figure 10 shows increased values of cohesion and decreased values of angles of internal friction when the percentage of crusher dust increased. Cohesion increased from 17.1 to 69.4 psi. and the angle of internal friction decreased from 34.8 to 23.5 degrees when the percentage of crusher dust increased from 0 to 100 percent.

Bituminous-Concrete Mixtures within ASTM Specifications

Triaxial test results showing the relationship between cohesion and angle of internal friction and percent of crusher dust in the fine aggregate for bituminous-concrete mixtures within ASTM specifications are

presented in Figure 11. Figure 11 shows increased values of cohesion and angle of internal friction when the percentage of crusher dust in the fine aggregate was increased. Cohesion increased from 33.0 to 41.5 psi. and the angle of internal friction increased from 37.4 to 46.5 degrees when the percentage of crusher dust in the fine aggregate increased from 0 to 100 percent.

The data obtained from the extraction tests on the controlled dense-graded bituminous-concrete mixtures are presented in Table 13 in Appendix B and shown graphically in Figure 12. Figure 12 shows the distribution of asphalt between the coarse aggregate and fine aggregate portions of the bituminous-concrete mixtures, and the relation of this asphalt distribution to the triaxial strength characteristics of these mixtures when the percentage of crusher dust in the fine aggregate was changed.

The plotted data in Figure 12 show that the amount of asphalt coating the coarse aggregate decreased from 3.5 to 2.4 percent when the percentage of crusher dust increased from 0 to 75 percent. However, an increase from 75 to 100 percent of crusher dust in the fine aggregate resulted in an increase of asphalt coating the coarse aggregate from 2.4 to 3.0 percent. The amount of asphalt coating the fine aggregate fraction of the controlled dense-graded bituminous-concrete mixtures increased from 5.5 to 7.6 percent when the percentage of crusher dust in the fine aggregate increased from 0 to 100 percent. However, with percentages of crusher dust from 75 to 100 percent the increase of asphalt coating the fine aggregate was relatively small (7.3 to 7.6 percent).

COHESION & ANGLE OF INTERNAL FRICTION

VS.

PERCENT CRUSHER DUST

BITUMINOUS-CONCRETE MIXTURES

(Controlled Dense-Graded)

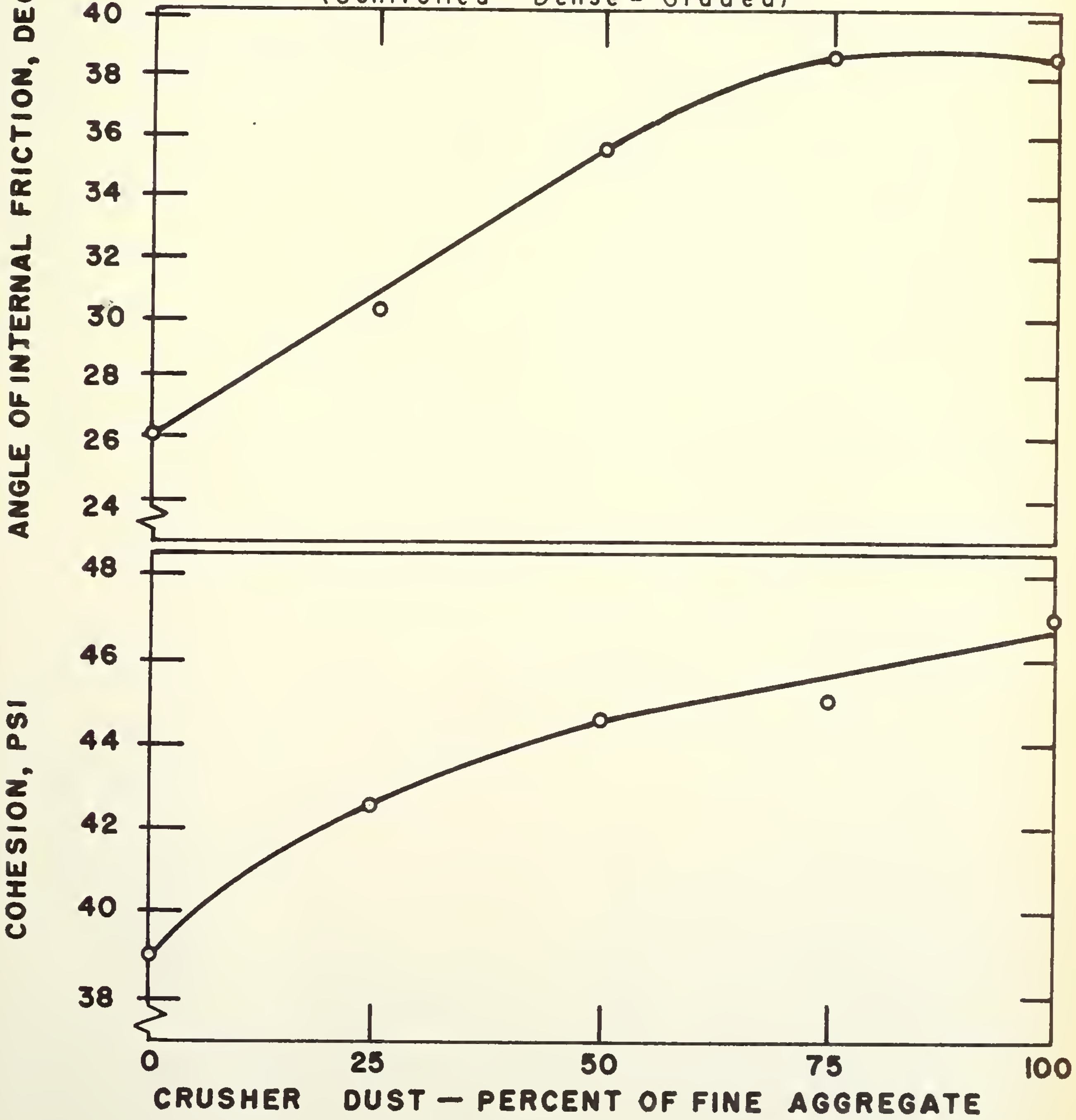


FIGURE 9

COHESION & ANGLE OF INTERNAL FRICTION
VS.
PERCENT CRUSHER DUST

SAND-ASPHALT MIXTURES

(Controlled Dense-Graded)

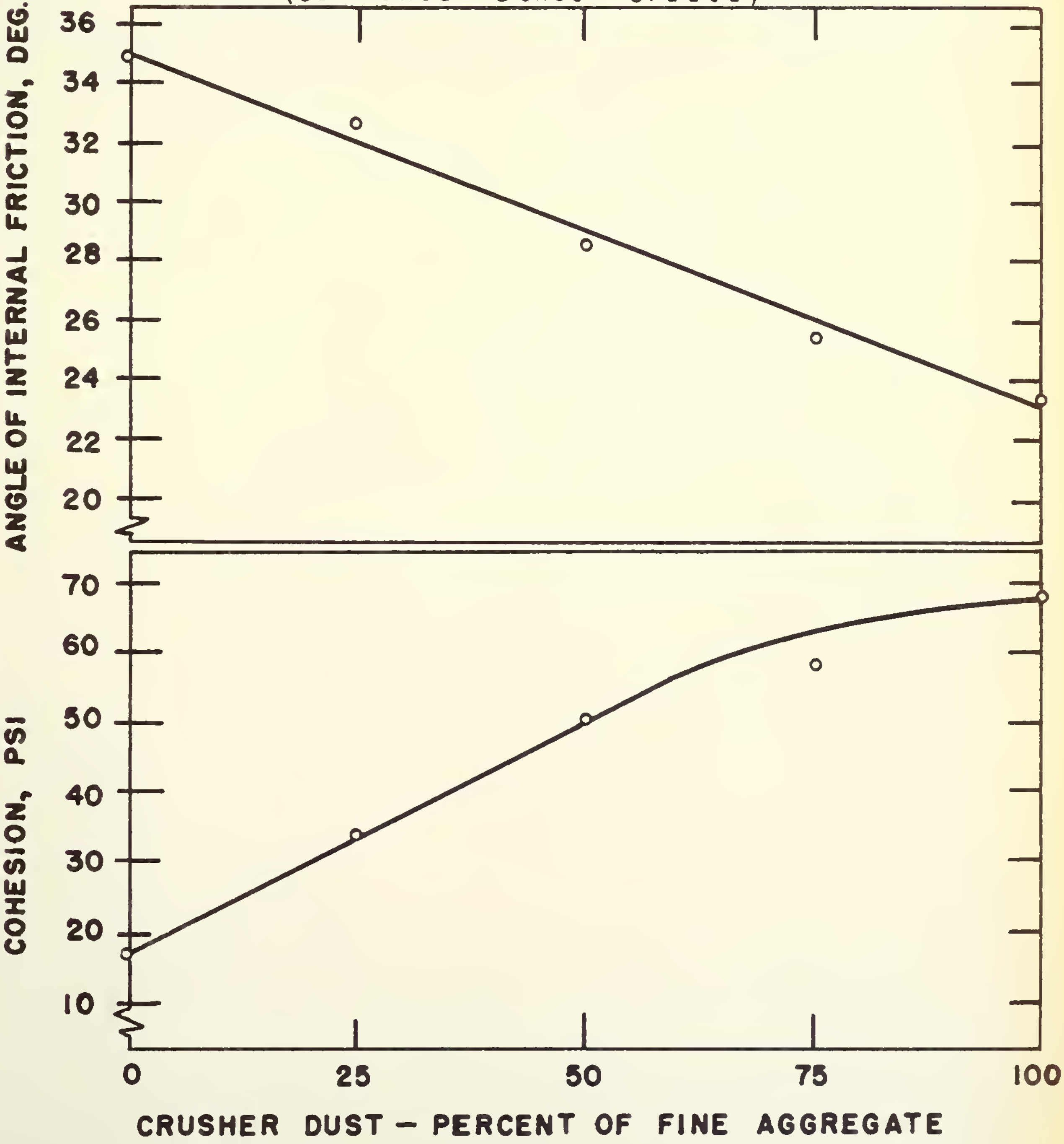


FIGURE 10

COHESION & ANGLE OF INTERNAL FRICTION
VS.
PERCENT CRUSHER DUST

CRUSHER DUST-NATURAL AGGREGATE BLENDS WITHIN ASTM SPECIFICATIONS
BITUMINOUS-CONCRETE MIXTURES

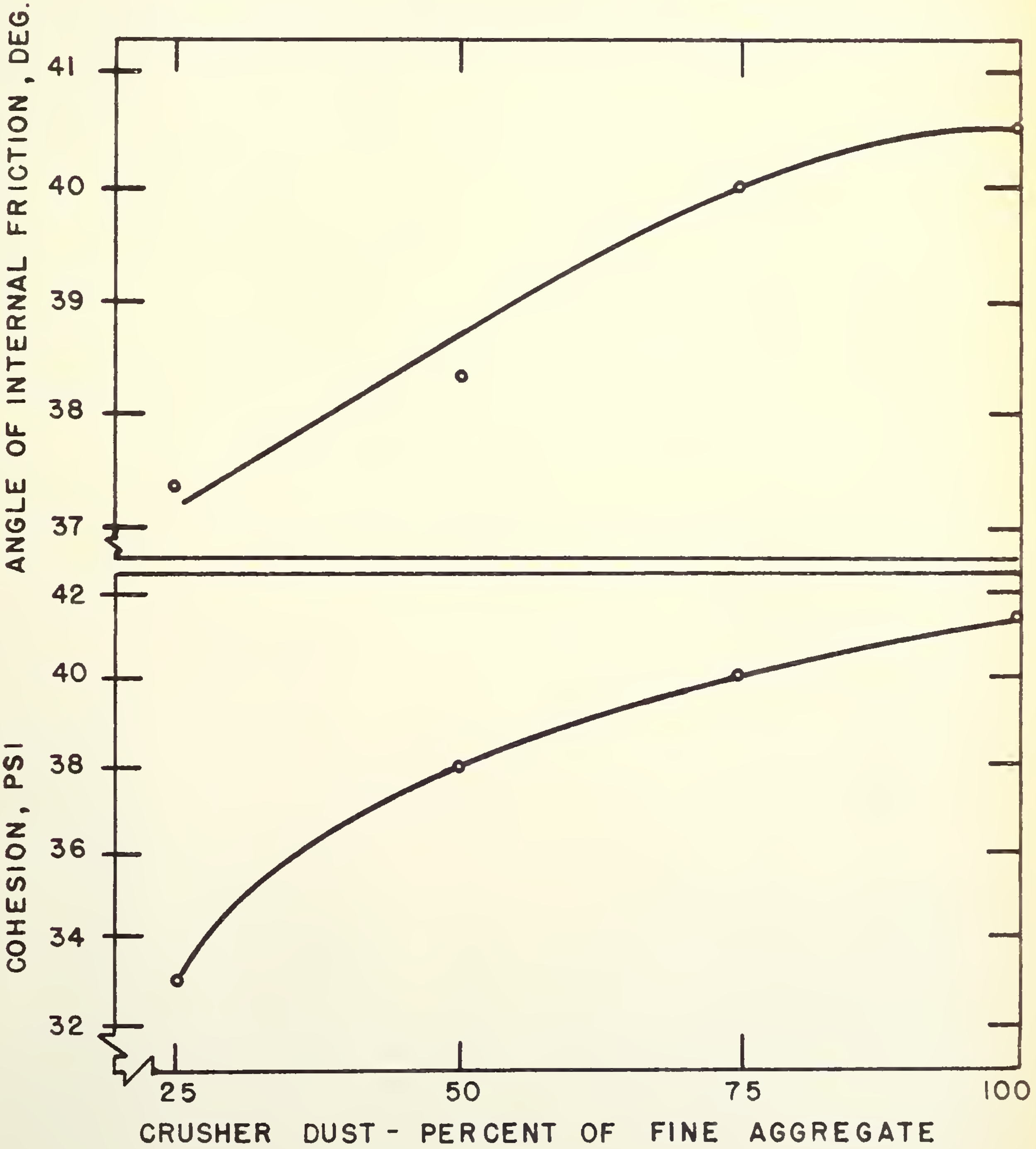


FIGURE 11

In Figure 12 the design asphalt contents of the controlled dense-graded sand-asphalt mixtures are plotted against percent of crusher dust in the sand. It should be repeated here that the controlled dense-graded sand-asphalt mixtures and the fine aggregate fraction of the controlled dense-graded bituminous-concrete mixtures consisted of the same aggregates and aggregate gradation. The range in amounts of asphalt coating the fine aggregate when percentage of crusher dust was varied was greater in the fine aggregate fraction of the controlled dense-graded bituminous-concrete mixtures than in the controlled dense-graded sand-asphalt mixtures. The amount of asphalt coating the fine aggregate portion of the controlled dense-graded bituminous-concrete mixtures exceeded the percentage of asphalt in the sand-asphalt mixtures with percentages of crusher dust greater than 50 percent.

Figure 12 shows increased amount of asphalt coating the fine aggregate and decreased amount of asphalt coating the coarse aggregate for the controlled dense-graded bituminous-concrete mixtures when the percentage of crusher dust in the fine aggregate increased from 0 to 75 percent; at the same time, cohesion and angles of internal friction increased for these mixtures. The angle of internal friction did not increase when these mixtures contained 75 to 100 percent of crusher dust in the fine aggregate and the amount of asphalt coating the coarse aggregate increased with this increase in percentage of crusher dust.

Figure 10 shows increased cohesion and decreased angle of internal friction when the percentage of crusher dust was increased in the controlled dense-graded sand-asphalt mixtures; at the same time, Figure 12 shows the design asphalt content to have increased for these mixtures.

DISTRIBUTION OF ASPHALT AND TRIAXIAL STRENGTH CHARACTERISTICS VS. PERCENT CRUSHER DUST

BITUMINOUS-CONCRETE MIXTURES

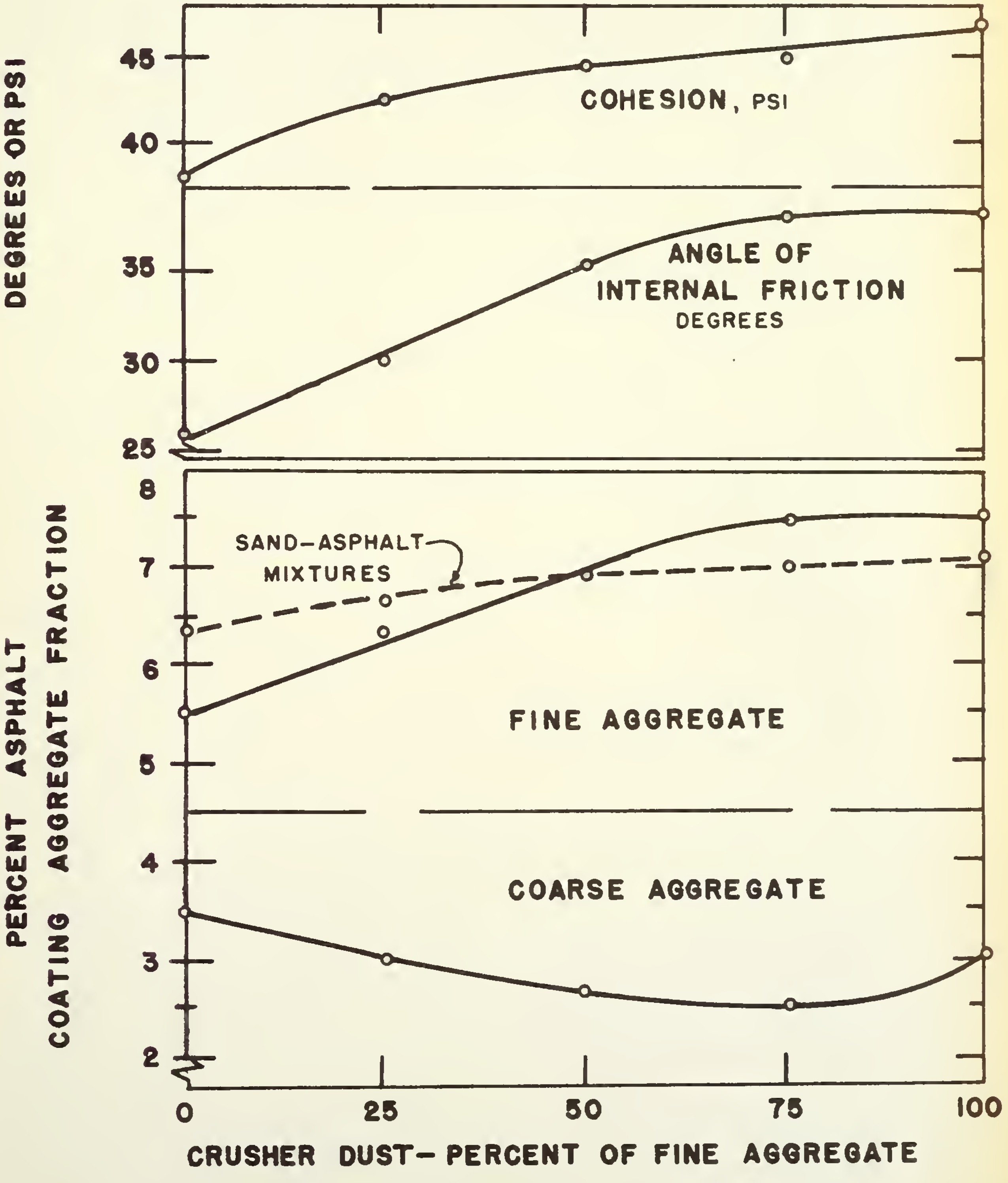


FIGURE 12

SUMMARY OF RESULTS AND CONCLUSIONS

The following summary of results from this investigation are presented. The results are limited to the types of bituminous surface mixtures employed in this investigation and to the methods of testing described herein. Because of the scope and nature of this study, these results have not been evaluated by testing similar materials under field conditions.

1. In general, the results from the laboratory tests used showed appreciable strength increases in the mixtures studied when the percentage of crusher dust in the fine aggregate was increased. That is to say, the compressive strength of each mixture increased, regardless of whether gravel coarse aggregate was incorporated into the mix or not, as the presence of crusher dust became more prominant in the fine aggregate. Figures 6 to 8 show that even a small percentage of crusher dust in the fine aggregate, 25 percent or so, increased the compressive strength of the mixtures over similar mixtures that contained all natural-sand fine aggregate.

2. Compressive strength values that resulted from ASTM tests on ASTM and Modified ASTM test specimens were the highest strength values obtained, and were followed in decreasing order by triaxial test and Marshall Stability values. These strength differences were due in part to variations in specimen size, specimen density, testing speed and testing temperature.

3. ASTM tests on ASTM and Modified ASTM test specimens resulted in compressive strength values of greater magnitude in the controlled dense-graded sand-asphalt mixtures than the lower and more equal values that resulted from these tests on controlled dense-graded and ASTM specifi-

cation-type bituminous-concrete mixtures. The compressive strength data from the triaxial test showed a lesser variance in strength values than the ASTM and Modified ASTM test data when the percentage of crusher dust varied. Marshall Stability values for the controlled dense-graded bituminous-concrete mixtures varied less and were greater at small percentages of crusher dust, 0 to 50 percent, in the fine aggregate when compared to the controlled dense-graded sand-asphalt mixtures and the bituminous-concrete mixtures within ASTM specifications.

4. The presence of crusher dust in the fine aggregate increased the design asphalt content of all the mixtures studied. The greatest increase in design asphalt content due to increased percentages of crusher dust in the fine aggregate was in the controlled dense-graded bituminous-concrete and sand-asphalt mixtures. A lesser increase in design asphalt content due to increased percentages of crusher dust in the fine aggregate was in the bituminous-concrete mixtures where the crusher dust-Indiana No. 17 sand fine aggregate grading varied within ASTM specifications.

5. Similar compressive strength characteristics were found from the tests used in this investigation for the controlled dense-graded and ASTM specification-type bituminous-concrete mixtures. Bituminous-aggregate mixture strength was approximately duplicated for these bituminous-concrete mixtures. The design asphalt contents of the bituminous-concrete mixtures within ASTM specifications were greater than those in the controlled dense-graded bituminous-concrete mixtures at lower percentages of crusher dust, 0 to 50 percent, in the fine aggregate; and in these two groups of mixtures with this percentage range of crusher dust in the fine aggregate, the bituminous-concrete mixtures within ASTM specifications were less densely graded than the controlled dense-graded

bituminous-concrete mixtures.

6. The causes for increased compressive strength in the controlled dense-graded bituminous-concrete mixtures and the bituminous-concrete mixtures within ASTM specifications seemed primarily due to the increased values of cohesion and angles of internal friction with increased percentages of crusher dust in the fine aggregate.

7. The cause for the increased compressive strength in the controlled dense-graded sand-asphalt mixtures seemed primarly due to the high increase in cohesion as compared to a relatively small effect resulting from a decrease in the angle of internal friction when the percentage of crusher dust in the fine aggregate increased. In other words, when the cohesion increased at the same time the angle of internal friction decreased, the over-all effect was increased compressive strength.

8. Triaxial strength characteristics of cohesion and angle of internal friction for the controlled dense-graded bituminous-concrete mixtures studied seemed to have been influenced by the distribution of asphalt between the coarse aggregate and fine aggregate fractions of these mixtures; this distribution of asphalt was influenced by the amount of crushed-gravel fine aggregate.

Figure 12 has shown that cohesion and angle of internal friction increased when the asphalt in the coarse aggregate fraction decreased. At the same time the asphalt in the coarse aggregate fraction decreased, the asphalt in the fine aggregate fraction increased by an amount equal to the loss of asphalt in the coarse aggregate fraction. These results could be explained by a theory of bituminous-aggregate mixture strength that angle of internal friction is largely dependent upon the characteristics and amount of relatively large aggregate (coarse aggregate) in

the mixture, and cohesion is largely dependent upon the characteristics of the fine aggregate and the amount of bituminous binder therein.

9. Generally, for all mixtures and compaction methods used in this investigation, except for the controlled dense-graded bituminous-concrete mixtures compacted by the Corps of Engineers' procedure, the density resulting from each compaction procedure for each mixture increased when the percentage of crusher dust in the fine aggregate increased; at the same time, the compressive strength of these mixtures increased. This increase in density seemed primarily due to the higher specific gravity and angularity of the crusher-dust fine aggregate when compared to the natural-sand fine aggregate.

10. The increased strength of bituminous surface mixtures made with crushed-gravel fine aggregate, or crusher dust when compared to similar mixtures made with natural-sand fine aggregate, was thought to be due to the angularity and surface texture of the crushed aggregate.

SUGGESTIONS FOR ADDITIONAL RESEARCH

The results from this investigation and several preceeding investigations suggest further studies of crushed-gravel fine aggregate in all types of bituminous-aggregate mixtures. Additional research could prove worthwhile on other types of bituminous-aggregate mixtures where crushed-gravel fine aggregate is used.

A specific goal in this research would be a "rule of thumb" method such that sands resulting from crushed gravel could be blended with a natural plant-run sand at given percentages to give some pre-determined strength properties of the bituminous surface mixtures made.

Additional study could further investigate the effect of the characteristics and amount of fine aggregate and aggregate gradation upon asphalt distribution in bituminous-concrete mixtures, and the resulting effect this has on triaxial strength characteristics of these mixtures.

Although angularity and surface texture of the crushed-gravel fine aggregate was an important strength-increasing property of crusher dust, it was also believed that the fines resulting from the gravel-crushing process have characteristics that influence strength. A further study could investigate the strength properties and characteristics of the fine material resulting from the gravel-crushing process.

APPENDIX A

DERIVATION OF RELATIONSHIP BETWEEN THE PLOT OF COMPRESSIVE STRENGTH VS. LATERAL PRESSURE AND MOHR'S RUPTURE ENVELOPE (19)

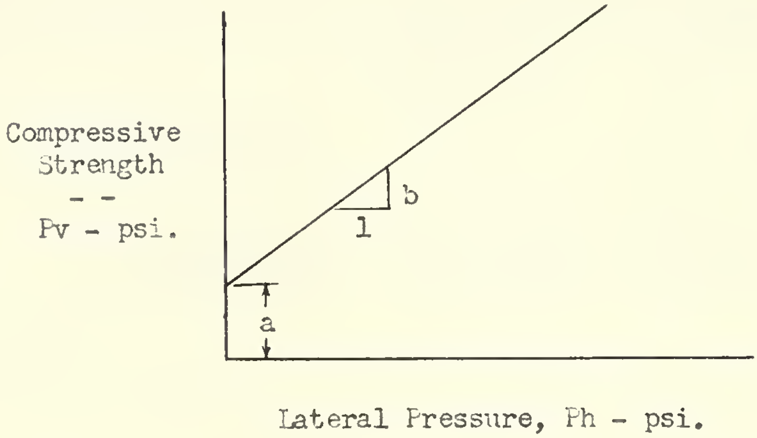


FIGURE 13. PLOT OF COMPRESSIVE STRENGTH VS. LATERAL PRESSURE

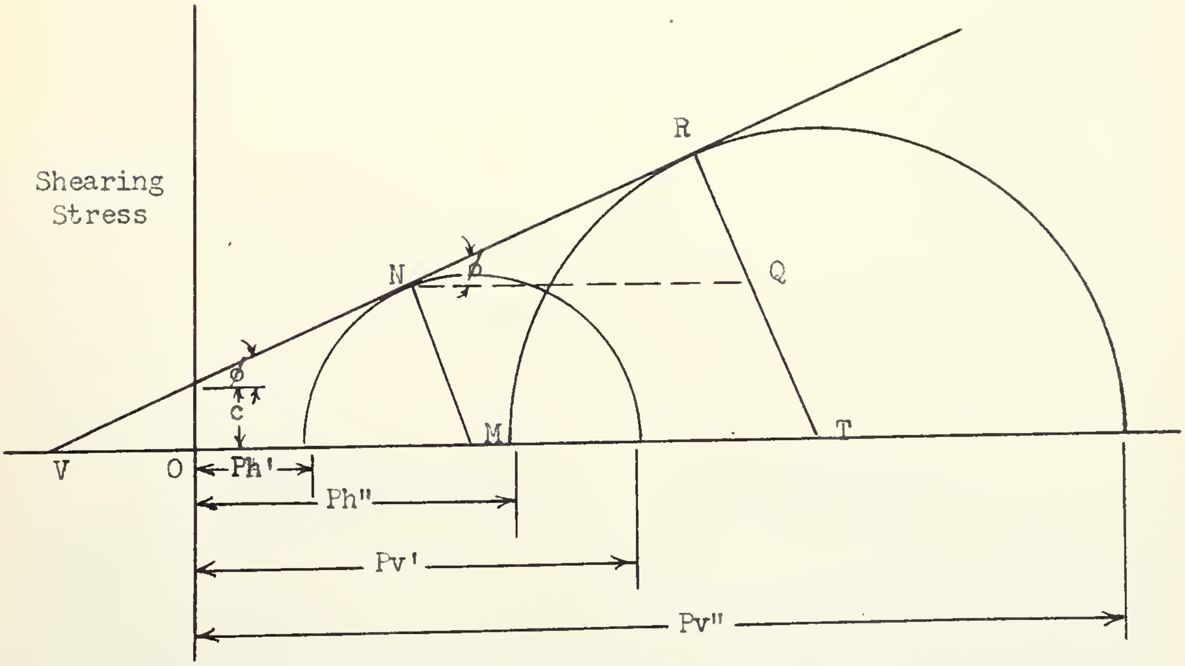


FIGURE 14. TYPICAL MOHR'S RUPTURE ENVELOPE

The equation of the linear line in Figure 13 is:

$$Pv = b\ Ph + a$$

Derivation of Equation of Sin ϕ

From Figure 14:

$$TR = Pv''/2 - Ph''/2 \qquad MN = Pv'/2 - Ph'/2 \qquad OT = Pv''/2 + Ph''/2$$

$$OM = Pv'/2 + Ph'/2$$

$$\text{Sin } \phi = \frac{RQ}{NQ} = \frac{TR - MN}{OT - OM}$$

$$= \frac{(Pv''/2 - Ph''/2) - (Pv'/2 - Ph'/2)}{(Pv''/2 + Ph''/2) - (Pv'/2 + Ph'/2)} = \frac{Pv'' - Ph'' - Pv' + Ph'}{Pv'' + Ph'' - Pv' - Ph'}$$

Where (from Figure 13):

$Pv'' =$ Pv of higher value $= b\ Ph'' + a$

$Pv' =$ Pv of lower value $= b\ Ph' + a$

Then:

$$Pv'' + Pv' = bPh'' + bPh' + 2a \quad \text{or} \quad Pv'' = bPh'' + bPh' + 2a - Pv'$$

$$\text{Sin } \phi = \frac{bPh'' + bPh' + 2a - Pv' - Ph'' - Pv' + Ph'}{bPh'' + bPh' + 2a - Pv' + Ph'' - Pv' - Ph'}$$

$$\frac{Ph''(b - 1) + Ph'(b + 1) - 2(Pv' - a)}{Ph''(b + 1) + Ph'(b - 1) - 2(Pv' - a)}$$

but $Pv' - a = bPh'$

$$\frac{Ph''(b - 1) + Ph'(b + 1) - 2bPh'}{Ph''(b + 1) + Ph'(b - 1) - 2bPh'}$$

$$\frac{Ph''(b - 1) - Ph'(b - 1)}{Ph''(b + 1) - Ph'(b + 1)}$$

Let $Ph'' = nPh'$, where n is any positive number.

$$\text{Sin } \phi = \frac{nPh'(b - 1)}{nPh'(b + 1)} \ \frac{Ph'(b - 1)}{Ph'(b + 1)} = \frac{(nPh' + Ph')\ (b - 1)}{(nPh' + Ph')\ (b + 1)}$$

Thus $\text{Sin } \phi = \dfrac{b - 1}{b + 1}$

Derivation of Equation for c

From Figure 14:

$$MN = Pv' - Ph'/2 \qquad OV = c \cot \phi \qquad OM = Pv' + Ph'/2$$

$$\sin \phi = \frac{MN}{VM} = \frac{MN}{OM + OV} = \frac{Pv' - Ph'/2}{Pv' + Ph'/2 + c \cot \phi}$$

But since $\sin \phi = \frac{b - 1}{b + 1}$:

$$\frac{b - 1}{b + 1} = \frac{Pv' - Ph'}{Pv' + Ph' + 2c \cot \phi}$$

$$(Pv' - Ph')\ (b + 1) = (Pv' + Ph' + 2c \cot \phi)\ (b - 1)$$

$$Pv'b + Pv' - Ph'b - Ph' = Pv'b - Pv' + Ph'b - Ph' + 2bc \cot \phi$$
$$- 2c \cot \phi$$

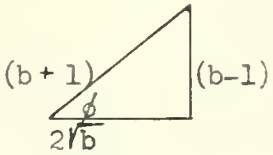
$$2\ Pv' - 2Ph'b = 2bc \cot \phi - 2c \cot \phi$$

However $Pv' - Ph'b = a$

$$a = c \cot \phi\ (b - 1)$$

$$c = \frac{a}{\cot \phi\ (b - 1)}$$

Since $\sin \phi = \frac{b - 1}{b + 1}$



$$\cot \phi = \frac{2\sqrt{b}}{b - 1}$$

Thus:

$$c = \frac{a}{\frac{2\sqrt{b}}{b-1}\ (b-1)}$$

$$c = \frac{a}{2\sqrt{b}}$$

APPENDIX B

This appendix presents in tabular form the laboratory test data which have been obtained in this investigation.

The data are given in the following order:

A. Corps of Engineers' Design Data.

B. Triaxial Test Data.

C. ASTM and Modified ASTM Test Data.

D. Asphalt Extraction Test Data.

TABLE 6

CORPS OF ENGINEERS' DESIGN DATA

BITUMINOUS-CONCRETE MIXTURES, CONTROLLED DENSE-GRADED						
PERCENT CRUSHER DUST	DESIGN ASPHALT CONTENT*	MARSHALL STABILITY lbs.	MARSHALL FLOW 1/100-in.	PERCENT VOIDS	PERCENT VOIDS FILLED WITH ASPHALT	UNIT WEIGHT lb/cu.ft.
0	4.6	1500	12.0	3.3	77	151.3
25	4.8	1790	11.7	3.5	75	150.9
50	4.9	2200	11.0	3.2	80	151.3
75	5.1	2190	11.8	3.2	80	151.0
100	5.5	2050	11.5	3.8	78	151.0
SAND-ASPHALT MIXTURES, CONTROLLED DENSE-GRADED						
0	6.3	860	10.0	6.0	70	144.7
25	6.6	1100	10.7	6.0	72	144.3
50	6.9	1410	11.0	5.8	73	146.5
75	7.1	2040	14.9	5.0	75	146.3
100	7.2	2425	16.0	5.5	75	145.7

* Design asphalt content given in terms of percent by weight of total aggregate.

TABLE 7

CORPS OF ENGINEERS' DESIGN DATA

CRUSHER DUST - NATURAL AGGREGATE BLENDS

WITHIN ASTM SPECIFICATIONS FOR BITUMINOUS-CONCRETE MIXTURES

PERCENT CRUSHER DUST	DESIGN ASPHALT CONTENT*	MARSHALL STABILITY lbs.	MARSHALL FLOW 1/100-in.	PERCENT VOIDS	PERCENT VOIDS FILLED WITH ASPHALT	UNIT WEIGHT lb/cu.ft.
0	-	-	-	-	-	-
25	5.4	650	15.4	3.9	74	144.1
50	5.5	1260	12.9	3.7	77	147.5
75	5.5	1720	13.2	3.0	79	148.8
100	5.6	2010	12.7	3.0	83	149.3

---

* Design asphalt content given in terms of percent by weight of total aggregate.

TABLE 8

TRIAXIAL TEST RESULTS

BITUMINOUS-CONCRETE MIXTURES, CONTROLLED DENSE-GRADED

Percent Crusher Dust	0		25		50		75		100	
Lateral Pressure psi.	15	30	15	30	15	30	15	30	15	30
Compressive Strength-psi.	153 157	188 193	173 181	221 213	206 196	251 241	214 208	262 260	216 220	272 262
Ave. Compressive Strength-psi.	155	190	177	217	201	246	211	261	218	267
b	45.5		45.5		45.5		45.5		45.5	
a	20.0		22.9		26.3		28.5		28.5	
sin ϕ	0.440		0.504		0.579		0.625		0.625	
ϕ, deg.	26.1		30.2		35.4		38.7		38.7	
c, psi.	39.0		42.7		44.5		45.0		47.0	

SAND-ASPHALT MIXTURES, CONTROLLED DENSE-GRADED

Percent Crusher Dust	0		25		50		75		100	
Lateral Pressure psi.	15	30	15	30	15	30	15	30	15	30
Compressive Strength-psi.	107 101	138 157	162 147	188 206	198 202	238 236	215 218	255 247	232 241	263 277
Ave. Compressive Strength-psi.	104	148	155	197	200	237	217	251	237	270
b	38.1		38.1		38.1		38.1		38.1	
a	21.8		20.6		18.2		16.6		15.2	
sin ϕ	0.572		0.539		0.476		0.434		0.398	
ϕ, deg.	34.8		32.7		28.5		25.8		23.5	
c, psi.	17.1		33.0		51.0		59.2		69.4	

TABLE 9

TRIAXIAL TEST RESULTS

CRUSHER DUST - NATURAL AGGREGATE BLENDS

WITHIN ASTM SPECIFICATIONS FOR BITUMINOUS-CONCRETE MIXTURES

Percent Crusher Dust	0		25		50		75		100	
Lateral Pressure psi.	15	30	15	30	15	30	15	30	15	30
Compressive Strength-psi.	- -	- -	153 175	207 217	190 178	238 226	199 193	217 273	211 197	251 258
Ave. Compressive Strength-psi.	-	-	164	212	184	232	196	245	204	254
b	-	-	135.0		135.0		135.0		135.0	
a	-	-	82.0		83.5		86.8		87.8	
sin ∅	-	-	0.607		0.618		0.643		0.650	
∅, deg.	-	-	37.4		38.2		40.0		40.5	
c, psi.	-	-	33.0		38.0		40.0		41.5	

TABLE 10

ASTM AND MODIFIED ASTM TEST RESULTS

CONTROLLED DENSE-GRADED BITUMINOUS-CONCRETE MIXTURES

ASTM TEST					
Percent Crusher Dust	0	25	50	75	100
Compressive Strength-psi.	223 216	259 265	284 278	325 343	380 364
Ave. Compressive Strength-psi.	219	262	281	334	372
Unit Weight lb./cu.ft.	147.1	148.5	149.1	149.7	150.5
	MODIFIED ASTM TEST				
Percent Crusher Dust	0	25	50	75	100
Compressive Strength-psi.	284 293	304 315	376 372	420 431	429 439
Ave. Compressive Strength-psi.	288	309	374	425	434
Unit Weight lb./cu.ft.	151.3	150.9	151.3	151.0	151.0

TABLE 11

ASTM AND MODIFIED ASTM TEST RESULTS

CONTROLLED DENSE-GRADED SAND-ASPHALT MIXTURES

ASTM TEST					
Percent Crusher Dust	0	25	50	75	100
Compressive Strength-psi.	261 257	334 322	427 433	495 492	570 561
Ave. Compressive Strength-psi.	259	328	430	494	566
Unit Weight lb./cu.ft.	141.0	143.2	146.5	147.5	148.0
MODIFIED ASTM TEST					
Percent Crusher Dust	0	25	50	75	100
Compressive Strength-psi.	278 284	351 342	385 391	488 494	512 525
Ave. Compressive Strength-psi.	281	346	388	491	518
Unit Weight lb./cu.ft.	144.7	144.3	146.5	146.3	145.7

TABLE 12

ASTM AND MODIFIED ASTM TEST RESULTS

CRUSHER DUST - NATURAL AGGREGATE BLENDS

WITHIN ASTM SPECIFICATIONS FOR BITUMINOUS-CONCRETE MIXTURES

ASTM TEST					
Percent Crusher Dust	0	25	50	75	100
Compressive Strength-psi.	- -	213 205	289 303	324 328	359 340
Ave. Compressive Strength-psi.	-	209	296	326	350
Unit Weight lb./cu.ft.	-	141.7	147.5	149.0	150.3

	MODIFIED ASTM TEST				
Percent Crusher Dust	0	25	50	75	100
Compressive Strength-psi.	- -	274 268	290 306	306 330	322 338
Ave. Compressive Strength-psi.	-	271	298	318	330
Unit Weight lb./cu.ft.	-	144.1	147.5	148.8	149.3

TABLE 13

ASPHALT EXTRACTION TEST RESULTS

CONTROLLED DENSE-GRADED BITUMINOUS-CONCRETE MIXTURES

Percent Crusher Dust	0	25	50	75	100
Design Asphalt Content (Percent Aggregate Wt.)	4.6	4.8	4.9	5.1	5.5
Design Asphalt Content (Percent Total Mix)	4.4	4.6	4.7	4.9	5.2
Percent Asphalt in Mix Coating Coarse Aggregate	34	28	24	22	24
Percent Asphalt in Mix Coating Fine Aggregate	66	72	76	78	76
Percent Asphalt Coating Coarse Aggregate (Percent of Coarse Aggregate Wt.)	3.5	3.0	2.7	2.4	3.0
Percent Asphalt Coating Fine Aggregate (Percent of Fine Aggregate Wt.)	5.5	6.3	6.8	7.3	7.6

LIST OF REFERENCES

1. American Association of State Highway Officials, "The Determination of the Percentage of Bitumen in Bituminous Mixes", AASHO Designation: T-5837, Standard Specifications for Highway Materials and Methods of Sampling and Testing, Part II, Washington, D.C., 1950.

2. American Society for Testing Materials, "Compressive Strength of Bituminous Mixtures (Tentative)", ASTM Designation: D1074-52T, ASTM Standards on Bituminous Materials for Highway Construction, Waterproofing, and Roofing, April 1953.

3. American Society for Testing Materials, "Tentative Specifications for Hot-Mixed, Hot-Laid, Asphaltic Concrete for Base and Surface Courses", ASTM Designation: D947-54T, 1954 Supplement to Book of ASTM Standards Including Tentatives, Part 3, 1955.

4. American Society for Testing Materials, Triaxial Testing of Soils and Bituminous Mixtures, Special Technical Publication 106, October 1949 and June 1950.

5. The Asphalt Institute, Manual on Hot-Mix Asphaltic Concrete Paving, 1948.

6. Barber-Greene Company, Bituminous Construction Handbook, Aurora, Ill., May 1955.

7. Broome, D.C. and Child, R.O., The Testing of Bituminous Mixtures, Edward Arnold and Company, London, 1934.

8. Campen, W.H. and Smith, J.R.,"A Study of the Role of Angular Aggregates in the Development of Stability in Bituminous Mixtures", Proceedings, Association of Asphalt Paving Technologists, Vol. 17, 1948.

9. Carpenter, C.A., Goode, J.F., and Peck, R.A., "An Improved Triaxial Cell for Testing Bituminous Paving Mixtures", Proceedings, Association of Asphalt Paving Technologists, Vol. 20, 1951.

10. Cooley Gravel Company, Report on the Development of a 3/8" Crushed Asphalt Aggregate, Denver, Colo., May 1954.

11. Corps of Engineers, U.S. Army, "Airfield Paving Design - Flexible Pavements", Engineering Manual for Military Construction, Part XII, Chapter 2, July 1951.

12. Draper, G.A., "Design and Construction of Bituminous Surfaces in Mississippi", Proceedings, The Montana National Bituminous Conference, September 1939.

13. Endersby, V.A., "The Measurement of Mechanical Stability of Bituminous Mixtures and Its Correlation with Surface Behavior", Proceedings, The Montana National Bituminous Conference, September 1939.

14. Goetz, W.H., "Comparison of Triaxial and Marshall Test Results", Proceedings, Association of Asphalt Paving Technologists, Vol. 20, 1951.

15. Goetz, W.H. and Chen, C.C., "Vacuum Triaxial Technique Applied to Bituminous-Aggregate Mixtures", Proceedings, Association of Asphalt Paving Technologists, Vol. 19, 1950.

16. Griffith, J.M., "Effects of High Pressure Tires on Bituminous Pavements", Proceedings, Association of Asphalt Paving Technologists, Vol. 20, 1951.

17. Griffith, J.M., "Evaluation of the Method of Asphalt Pavement Design Developed by the Corps of Engineers", Proceedings, Association of Asphalt Paving Technologists, Vol. 20, 1951.

18. Hennes, R.G. and Wang, C.C., "Physical Interpretation of Triaxial Data", Proceedings, Association of Asphalt Paving Technologists, Vol. 20, 1951.

19. Herrin, M., "Effects of Aggregate Shape on the Stability of Bituminous Mixtures", A Thesis submitted to Purdue University for the Degree of Doctor of Philosophy, May 1954.

20. Housel, W.S., "Internal Stability of Granular Materials", Proceedings, American Society for Testing Materials, Vol. 36, Part 2, 1936.

21. Hubbard, P., "Discussion on the Structural Design of Flexible Pavements", Proceedings, Highway Research Board, 1942.

22. Hubbard, P., "Effect of Aggregates Upon Stability of Bituminous Mixtures", Proceedings, American Society for Testing Materials, Vol. 29, Part 2, 1929.

23. Hveem, F.N., "Some Basic Factors and Their Effect on the Design of Bituminous Mixtures", Notes for a Short Course in Design and Control of Asphaltic Mixtures, Institute of Transportation and Traffic Engineering, University of California, February 1949.

24. Hveem, F.N., "Gradation of Mineral Aggregates for Dense-Graded Bituminous Mixtures", Proceedings, Association of Asphalt Paving Technologists, Vol. 11, 1940.

25. Hveem, F.N. and Vallerga, B.A., "Density Versus Stability", Proceedings, Association of Asphalt Paving Technologists, Vol. 21, 1952.

26. Kriege, H.F. and Gilbert, L.C., "Some Factors Affecting the Resistance of Bituminous Mixtures to Deformation Under Moving Wheel Loads", Proceedings, Association of Asphalt Paving Technologists, December 1933.

27. Martin, J.R. and Layman, A.H.Jr., "Hot-Mix Asphalt Design Studies", Engineering Experiment Station, Oklahoma A. and M. College, Pub. No. 75, 1950.

28. McFadden, G. and Ricketts, W.C., "Design and Field Control of Asphaltic Paving Mixtures for Military Installations", Proceedings, Association of Asphalt Paving Technologists.

29. McLaughlin, J.F., "An Investigation of the Properties Measured by the Marshall Test", A Thesis submitted to Purdue University for the Degree of Master of Science in Civil Engineering, January 1953.

30. McLaughlin, J.F. and Goetz, W.H., "Comparison of Unconfined and Marshall Test Results", Proceedings, Association of Asphalt Paving Technologists, Vol. 21, 1952.

31. McLeod, N.W., "Rational Design of Bituminous Paving Mixtures with Curved Mohr Envelopes", Proceedings, Association of Asphalt Paving Technologists, Vol. 21, 1952.

32. Nappe, S.L., "Mechanical Stability of Bituminous Mixtures: A Summary of the Literature", Proceedings, Association of Asphalt Paving Technologists, Vol. 22, 1953.

33. Nijboer, L.W., Plasticity as a Factor in the Design of Dense Bituminous Road Carpets, Elsevier Publishing Company, Inc., New York-Amsterdam-London-Brussels, 1948.

34. Pauls, J.T. and Carpenter, C.A., "Mineral Aggregates for Bituminous Construction", Symposium on Mineral Aggregates (1948), American Society for Testing Materials, Special Technical Publication No. 83, 1948.

35. Pauls, J.T. and Rex, H.M., "Design Problems Encountered in the Use of Local Aggregates", Proceedings, Association of Asphalt Paving Technologists, Vol. 18, February 1949.

36. Rice, J.M. and Goetz, W.H., "Suitability of Indiana Dune, Lake and Waste Sands for Bituminous Pavements", Proceedings, Association of Asphalt Paving Technologists, Vol. 18, February 1949.

37. Rogers, G.E., "A Study of the Influence of Aggregate Gradation on the Stability of Bituminous Mixtures", A Thesis submitted to Purdue University for the Degree of Master of Science in Civil Engineering, April 1948.

38. Shaub, J.G. and Humphries, T., "Resurfacing of Old Pavements with Asphaltic Concrete", Proceedings, Association of Asphalt Paving Technologists, Vol. 15, December 1943.

39. Shelburne, T.E., "Bituminous Surface Treatment", Engineering Experiment Station, Research Series Bulletin No. 32, Purdue University, 1941.

40. Skidmore, H.W., "Fine Aggregate in Bituminous Mixtures", Proceedings, American Society for Testing Materials, Vol. 29, Part 2, 1929.

41. Smith, V.R., "Triaxial Stability Method for Flexible Pavement Design", Proceedings, Association of Asphalt Paving Technologists, Vol. 18, 1949.

42. Spielmann, P.E. and Hughes, A.C., Asphalt Roads, Vol. V, Edward Arnold and Company, London, 1936.

43. State Highway Department of Indiana, Standard Specifications for Road and Bridge Construction and Maintenance, 1952.

44. Steele, D.C., "Mineral Aggregates for Asphalt Highway Surfaces", Materials, The Asphalt Institute Research Series No. 5, November 1939.

45. Stevens, D.E., "Fundamentals of Stability Testing of Asphalt Mixes", Proceedings, Association of Asphalt Paving Technologists, Vol. 2, January 1953.

46. Taylor, D.W., Fundamentals of Soil Mechanics, John Wiley and Sons, Inc., New York, 1950.

47. Terzaghi, K. and Peck, R.B., Soil Mechanics for Engineering Practice, John Wiley and Sons, Inc., New York, 1952.

48. Vokac, R., "Compression Testing of Asphalt Paving Mixtures", Proceedings, American Society for Testing Materials, Vol. 36 - Part 2 and Vol. 37 - Part 2, 1936 and 1937.

49. Vokac, R., "Correlation of Physical Characteristics with the Surface Behavior of Asphaltic Mixtures", Proceedings, Technical Sessions, Association of Asphalt Paving Technologists, New Orleans, La., 1937.

50. Waterways Experiment Station, Construction Inspectors Manual for Flexible Pavements, Prepared for the Office of Chief of Engineers, Vicksburg, Miss., August 1954.